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Exploration of Terminal Procedures Enabled by NASA WakeVAS Technologies

Clark R. Lunsford, Arthur P. Smith III, Wayne W. Cooper Jr., Anand D. Mundra, Amy E. Gross, Laurence F. Audenaerd, and Bruce E. Killian

The MITRE Corporation
Center for Advanced Aviation System Development
McLean, Virginia

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Section 1

Introduction

The National Aeronautics and Space Administration (NASA) tasked The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) to investigate potential air traffic control (ATC) procedures that could benefit from technology used or developed in NASA's Wake Vortex Advisory System (WakeVAS). The task also required developing an estimate of the potential benefits of the candidate procedures. The main thrust of the investigation was to evaluate opportunities for improved capacity and efficiency in airport arrival and departure operations. Other procedures that would provide safety enhancements were also considered.

The purpose of this investigation was to provide input to the WakeVAS program office regarding the most promising areas of development for the program. A two-fold perspective was desired: First, identification of benefits from possible procedures enabled by both incremental components and the mature state of WakeVAS technology; second identification of procedures that could be expected to evolve from the current Federal Aviation Administration (FAA) procedures. The evolution of procedures should provide meaningful increments of benefit and a low risk implementation of the WakeVAS technologies.

The ATC procedures analyzed in this investigation should be considered at the stage of concept exploration. Any procedures that show benefits will need to be evaluated further by NASA, FAA and the stakeholders with respect to development and implementation risks prior to being recommended for development.

The intended audience of this document is assumed to have a general understanding of ATC arrival and departure procedures and of wake turbulence behavior.

The accuracy of the information is the responsibility of the authors only. The contents of this document express the opinions of the authors only, and do not reflect any official position or commitment of NASA, the FAA or U.S. Department of Transportation.

1.1 Approach

WakeVAS has many component technologies. The approach used in this investigation was to look at each of the WakeVAS technologies individually and to design ATC procedures that take advantage of the information provided by WakeVAS technology. The order in which the technologies were considered was based on their current maturity and likely implementation timeframe. The ATC procedures were designed in evolutionary steps, each step using progressively more technology, up to and including the use of all of the WakeVAS technologies.

Potential wake vortex related ATC procedures were considered for arrival and departure operations at airports with single runways, closely spaced parallel runways (CSPR), and intersecting runways. The starting point for each set of procedure steps were the FAA procedure currently used for single runways, the FAA near term proposal for CSPR arrivals, or the FAA mid-term proposal for CSPR departures. Many evolutionary procedure steps were identified during this investigation. Due to resource and time constraints, a smaller subset of procedure steps needed to be selected for detailed capacity and benefit analysis. Seven steps were considered the best candidates for further analysis: four steps implementing progressively more mature technology applied to CSPR arrivals, and one step each for single runway arrivals, single runway departures, and CSPR departures. The final evolutionary step for each was the implementation of the full WakeVAS.

Eighteen airports were selected for analysis. Depending on the particular procedure, a subset of these airports was chosen to analyze the potential capacity improvement and benefit of that procedure. Information on traffic mix, weather, and operations was collected from Enhanced Traffic Management System (ETMS) and Aviation System Performance Measurements (ASPM) and used in the capacity/benefit calculations.

1.2 Document Organization

Section 2 of this report reviews the WakeVAS and related technologies. Section 3 discusses the procedures that can take advantage of these technologies. Section 4 describes a subset of these procedures selected for a more detailed analysis. Section 5 describes the methodology used for estimating the capacity increases and benefits that could be achieved from the procedures and technologies. The quantitative benefit results of this task have been delivered separately to the WakeVAS program office. Section 6 envisions a concept of use of one of the procedures. Section 7 summarizes the significant findings from this report and discusses the necessary next steps.

A more detailed description of each of the ATC arrival and departure procedures discussed in this document is provided in Appendix A. Appendix B provides a summary of ATC departure rules, derived from FAA Order 7110.65. Aircraft characteristics used in determining aircraft cluster assignments are listed in Appendix C.

Section 2

Summary of Technologies Applicable to Developing Wake Vortex Related Procedures

This section outlines the WakeVAS components at a very high level as they may relate to the development of new ATC procedures, and describes the authors' assumptions about the potential evolution of these components with respect to their incremental implementation in the National Airspace System (NAS). This supports the primary purpose of this report to describe ATC procedures that could be derived from the WakeVAS technologies developed by NASA. The WakeVAS Concept of Operations has been described by Rutishauser [1]. The WakeVAS concept is under further development as a part of the NASA Virtual Airspace Modeling and Simulation (VAMS) Project.

In addition, there are also currently several other technologies in development that may either *enable* the realization of the benefits of the WakeVAS system, or may further *enhance* its potential benefits. A brief summary of these technologies is included in this section. The technologies that *enable* WakeVAS benefits will be considered as part of the domain of the WakeVAS development effort. Other technologies that could *enhance* WakeVAS benefits are considered optional, but are included here to provide a more complete consideration of the technology development effort.

As stated in the FAA/NASA Joint Research Management Plan [2], these technologies are classified based on their relative time-horizon until implementation (i.e., Near-Term, Mid-Term and Far-Term).[1]

- **Near-Term**: technologies that are currently available and being implemented in the field with initial deployment and benefits ranging in the 0-4 years timeframe. This does not include any technology that is not currently scheduled for implementation.
- **Mid-Term**: technologies being prototyped over the next three years that can be implemented without significant modifications to current pilot or controller operating procedures. The lead time until these technologies are initially deployed ranges from 5-7 years.
- **Far-Term**: technologies that are currently in design phase. Typically, either no prototype will be available over the next three years, or the implementation of the technology would significantly change the current controller or pilot operating

1 Note that there is no specific mapping from these categories to the NASA Technology Readiness Levels (TRLs).

practices. These technologies are forecast to begin deployment more than seven years in the future.

The technologies to be described below fall under six basic categories:

- WakeVAS Technologies for real-time weather and wake vortex measurement and prediction
- Five other technologies that enable or enhance WakeVAS benefits
  - Approach Spacing Technologies
  - Communication Technologies
  - Visualization Technologies
  - Separation Monitoring and Assurance Technologies
  - Navigation and Surveillance Technologies

The programmed or potential developments associated with each category are described in more detail below. For each category, the basic concept is discussed along with the current status, some critical requirements and associated risks of each technology. Most descriptions are generic, and are exemplified by specific systems as appropriate. Each category has systems that are currently being deployed in the field, and/or research programs that build upon earlier technology specifically targeting one of the three development stages. In some cases, current operational systems are identified as possible platforms for the addition of specific new features related to wake vortex avoidance. These research programs or scheduled operational systems are discussed under each technology category.

2.1 WakeVAS Technologies for Real-Time Weather and Wake Vortex Measurement and Prediction Technologies

These technologies comprise the complete WakeVAS system concept, and potentially will be fielded over several stages of evolution. This system will provide real-time wake and wind information, both current and predicted, for implementing specific procedural concepts. Implementing specific approach or departure procedures, as discussed later in this document, would depend on the availability and accuracy of wake and wind information. These technologies are described using the architecture and design developed for the Aircraft Vortex Spacing System (AVOSS), a prototype system developed by NASA as part of the Terminal Area Productivity Program (TAP). AVOSS development culminated in a wake vortex system test facility at DF W airport in 1997, and a field trial of the system in 1999-2000 [3]. WakeVAS is the current NASA concept incorporating AVOSS technology.

2.1.1 WakeVAS Weather Sensor Subsystem *Mid- to Far-Term*

This WakeVAS subsystem will measure wind parameters such as wind speed, wind direction, wind shear and atmospheric turbulence within airspace of concern in the terminal area. The AVOSS test facility at DFW fused data from the following sensors: (1) a radar wind profiler, (2) two Sound Detection and Ranging (SODAR) sensors, (3) a nearby Terminal Doppler Weather Radar (TDWR), (4) a 45 meter high meteorological tower (met tower) and (5) a Radio Acoustic Sounding System (RASS). A vertical profile of winds was developed from a combination of the radar wind profiler, SODARs, TDWR and meteorological tower data. A measure of atmospheric turbulence (i.e., Eddy Dissipation Rate [EDR]) was developed from wind and thermal data collected from different levels of the met tower. Temperature measurements from the met tower and RASS were used to develop a vertical temperature profile [3].

A prerequisite for terminal area weather systems is the capability to obtain accurate data at the required granularity for the airspace of concern. The Integrated Terminal Weather System (ITWS) may provide the necessary capabilities for this WakeVAS component. ITWS provides a forecast of terminal weather conditions for the next 20 minutes, based on a fusion of various FAA and National Weather Service (NWS) sensors, downlinked aircraft meteorological data, and other NWS weather model data. An experimental enhancement of the ITWS system for wake related application was field tested at DFW in 1999 and 2000.

ITWS is currently being deployed in the NAS. The current version may not currently contain all of the capabilities that may be required by this WakeVAS subsystem, but will allow additional enhancements required for wake measurement and modeling. The reliability and accuracy of the sensors and the required measurement granularity level for wake turbulence applications have not yet been precisely specified, but will be determined in the future as part of the operational analysis required to fully develop particular procedures.

2.1.2 WakeVAS Weather Prediction Subsystem *Mid- Far-Term*

This WakeVAS subsystem is expected to provide continuous prediction of wind speed, direction, shear, and turbulence index across an altitude profile up to 10,000 feet within approximately 20 nmi of a given airport. This system is intended to provide a reliable confidence interval for these weather forecasts. This information will then be used for "go/no go" decisions for specific terminal approach or departure procedures, and for input to wake prediction for wake-prediction dependent procedures. Appropriate algorithms must be developed and validated to provide predictions that satisfy the operational requirements of the corresponding terminal procedure. Ultimately, procedures that depend on wake transport and decay will need reliable predictions of wind speed, wind direction and atmospheric turbulence. Moreover, the procedure-specific confidence intervals for each weather parameter prediction must be established to ensure operational acceptance. Currently work is underway by MIT Lincoln Laboratories to develop wind prediction algorithms as part of the development of the proposed FAA mid-term departure procedure for CSPR. The German Air Navigation Services, Deutsche Flugsicherung (DFS), has produced the Wake Vortices Warning System (WVWS) that includes a prediction of cross-winds based on a statistical analysis of historical winds. The WVWS has been developed for application at Frankfurt International Airport [4].

In this document, two phases of weather prediction capability are assumed, and are called *WakeVAS-Wx1* and *WakeVAS-Wx2*. WakeVAS-Wx1 is meant to denote the capability to provide wind prognosis over a required time frame. Knowledge of wind behavior and potential wind forecasting capabilities are better understood at this time than those for other weather parameters that may also affect wake behavior (e.g., atmospheric turbulence). The capability to predict these latter parameters is grouped under a category called WakeVAS-Wx2. The two-phase nomenclature is intended to indicate an evolutionary order of technology maturity for operational use.

2.1.3 WakeVAS Wake Detection Subsystem *Far-Term*

This WakeVAS subsystem will be designed to detect wakes in real time for all appropriate conditions required for procedural use. It may also be required to produce reliable measurement of wake circulation strength in order to produce maximum usable benefits. Field testing at DFW in 1999 and 2000 [5] has made progress towards certifying a sensor suite and post-processing algorithms for reliable real-time wake detection. The WakeVAS program is expected to develop a sensor suite to provide robust real-time wake detection appropriate for operational use by targeted procedures.

Sensors used for wake detection include the following:

- Light Detection and Ranging (LIDAR) sensors, both Continuous Wave and Pulsed variants, that can detect wakes above ground level (AGL) at angles offset from the aircraft path. These systems can be used at distances up to several thousand feet from the wake being measured.
- Wake SODAR sensors that can detect wakes several hundred feet vertically above the sensor.
- Wind Lines, consist of rows of wind anemometers mounted on poles that are configured to measure winds in all three directions in order to detect wakes near ground level.

Currently, no sensors exist with the ability to detect wakes up the glide slope (e.g., at 3000 feet AGL) under very low ceiling conditions with high reliability and availability. SODARS can be used in cloudy conditions, but have limited altitude coverage and may be affected by ambient noise levels to provide necessary coverage. LIDARs are inhibited from detecting wakes through clouds or fog, and have reduced effectiveness in clear dry weather conditions.

To provide full coverage of the area where aircraft would be spaced closer than current separation standards, departures may require coverage up to about 500-1000 feet AGL, assuming a minimum course divergence of 15 degrees after liftoff. Arrivals would also require coverage up to as high as 4500 feet AGL. This conceivably would require wake detection out to the earliest point where current vertical (1000 feet) or in-trail separation (3 nmi) is lost on final approach.

It should be noted that real-time wake detection may not be necessary for procedures that use predetermined limits on wake behavior based on extensive historical weather and wake data collection. That is, for a specific aircraft weight class, accurate wind and turbulence predictions may be sufficient to predict the location of any resultant wake to be within a three-dimensional protected airspace volume. These protected airspace volumes would be based on the analysis of a large number of historical wakes and weather measurements. The operational use of such protected airspace volumes must also consider the prediction accuracy of the required weather parameters.

In such a concept, the protected airspace volume could in principle also change over the time from wake generation until the latest expected time of wake decay. To assure safe separation, the expected geometry and movements of this protected airspace must be predetermined for any future terminal procedure that provides separation closer than current standards.

A farther term enhancement to this basic concept would be a new procedure that uses a certain maximum limit of vortex strength above background levels. In this enhancement, the protected airspace volume must also include appropriately estimated sub-volumes where the wake would be expected to be less than a specified maximum circulation strength at each point in time.

One way to use a real-time wake detection system would be to provide a real-time safety net to indicate when a specific wake is behaving outside the protected wake airspace volume that would provide limited advance warning to the trailer aircraft. But this usage should only produce very infrequent warnings, as the protected wake airspace volume should be designed so that it contains wakes for all measured cases, under the specified weather conditions.

2.1.4 WakeVAS Wake Prediction Technology *Far-Term*

This WakeVAS subsystem is expected to provide robust real-time prediction for appropriate look-ahead times of the lateral and vertical transport limits and circulation target strengths for aircraft wakes generated in the airspace volumes being monitored for a specific procedure.[2] As indicated in the next paragraph, wake detection technology must be developed concurrently with wake prediction technology for operational use. Implementation risks include the requirement that analytical models would need to provide statistically and operationally robust predictions of maximum lateral and vertical wake transport as a function of weather (e.g., winds, turbulence) and aircraft parameters (e.g., aircraft type, weight).[3] Of course, the operational bounds on maximum transport must be validated with field collection of wakes. More advanced procedural concepts would, as discussed above, require the robust estimation of the three-dimensional airspace volumes that contain the wakes and potentially show the evolution of this protected volume until the time at which it has decayed to below background turbulence levels.

As per an established International Federation of Air Line Pilots' Associations (IFALPA) position [6], it is assumed in this paper that whenever a real-time wake prediction capability is used, it would be accompanied by a real-time wake detection capability. In addition, WakeVAS Wx1 and WakeVAS Wx2 capabilities would be available for operational use before a robust real time Wake Prediction and Wake Detection system. Once these latter capabilities are available, the WakeVAS system would be considered to be fully matured, and is referred to as *WakeVAS-PD*.

Effectively, our assumptions regarding the potential evolution of WakeVAS products implies that it should be possible to develop operationally meaningful descriptions of wake behavior based on wind prognosis (WakeVAS-Wx1) alone, and later with other weather parameters (WakeVAS-Wx2), without necessarily being accompanied by an adjunct real time wake detection and prediction system (WakeVAS-PD). It also expects that once the full fledged WakeVAS system with wake detection and prediction (WakeVAS-PD) becomes available for real time use, the earlier products based on WakeVAS-Wx1 and WakeVAS-Wx2 could be further enhanced. This is certainly the premise on which the current FAA mid-term product is based, which hopes to use a wind prognosis system for departures from closely spaced parallel runways. Whether other more complex wake related procedures can indeed be based on such incremental spin-offs from the WakeVAS program should be determined through further analysis.

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2 The maximum circulation strength allowed for a specific procedure may either be set to be equivalent to an appropriate level of background turbulence (e.g., 70 m^2/sec), or in farther term concepts, be based on the largest circulation strength that can safely be encountered by a specific trailing aircraft.

3 Note: the WVWS concept for Frankfurt uses ground wind measurements to measure maximum lateral wake transport only.

2.1.5 WakeVAS Human-Machine Interface *Mid- to Far-Term*

This interface is required to integrate the information developed by all of the above WakeVAS subsystems into a comprehensive display of the current and projected status of an intended procedure usage for potential users, including:

- Air Traffic Control Tower (ATCT)
- Terminal Radar Approach Control (TRACON)
- The flight deck (potentially for farther-term applications)

Other changes may also be needed, such as controller aides (e.g., spacing tools), to realize the benefits of a particular procedural concept. Integration of information for anticipated changes in the arrival and departure capacity into the Traffic Flow Management System may be needed for operational efficiency. The reliable prediction of future availability ("go/no go") of any procedure as well as the reliable prediction of variable spacing for procedures requiring variable spacing will be required for the potential implementation of this system as a whole. Extensive research into controller Human-Machine Interfaces (HMI) have been conducted for other applications, and can be exploited as part of the development of this interface technology for specific procedural applications. The acceptance of any future approach or departure procedure depends greatly upon controller and pilot acceptance and usage that will be a function of the interface design, training procedures and intended operational use.

2.2 Approach Spacing Technologies

These tools are designed to enable the realization of desired in-trail spacing values. Some WakeVAS concepts may rely on a set of separation rules or values more complex than is used currently. In such cases, appropriate approach spacing tools may be needed to realize such separations, and would be considered as part of the WakeVAS technologies. In other cases, the tools may provide additional precision, and would be considered as *enhancing* rather than *enabling* WakeVAS benefits.

2.2.1 Controller Based Approach Spacing Tools *Mid- to Far-Term*

A controller-based approach spacing tool would provide an air-traffic controller the capability to improve the precision of in-trail spacing between aircraft during their approach in the TRACON. The concept for this tool could also be expanded to include the consideration of required diagonal spacing between adjacent aircraft on closely spaced parallel approaches. In order for the technology to be implemented, it may require the tactical use of metering to flow arrivals at the required rate into the TRACON. In addition, it would require the development of an operationally suitable HMI that would be well integrated in the existing radar display.

“Ghosting” technology, originally developed by The MITRE Corporation for use in the Converging Runway Display Aid (CRDA) [7, 30, 31], is part of the Automated Radar Terminal System (ARTS) system fielded in the NAS. It is currently being used as a controller spacing aid in several U.S. and Canadian facilities, notably STL, PHL and Calgary. This tool provides final approach controllers with the ability to see graphically on their radar display the required spacing to ensure safe separation for flights on converging approach courses. It is also used in Calgary for in-trail spacing. This type of tool is easiest to apply when the procedural concept can be implemented without foreknowledge of the final approach sequence. Since this tool is already in use in the NAS, the implementation risk of such a tool in a new application is relatively low.

Another approach, exemplified by the Active Final Approach Spacing Tool (aFAST) currently in the development phase by NASA, is to provide a tool to project and recommend a final approach sequence, well before the flights are near the merge point in the TRACON approach area. This type of technology may be needed where the procedural concept has specific in-trail spacing requirements that depend both on the equipment type of the leading and of the trailing aircraft, and where the separation procedure is otherwise too complex to be applied manually. Controller acceptance of such a decision aid, where the final approach sequence is generated before the traffic is merged, will require a significant change in current operating practice.

2.2.2 Flight Crew Based Approach Spacing Tools *Far-Term*

Similar to the controller based tools, this class of tools is intended to provide the flight crew of a trailing aircraft the ability to follow a leading aircraft with better achievement of required separation minima, either in-trail or diagonally from aircraft on the adjacent CSPR. A research project recently conducted by NASA, Advanced Terminal Area Approach Spacing (ATAAS), is one example of a flight crew-based approach spacing tool [8]. The concept is that the pilot would accept clearance to use the ATAAS tool and then comply with speed controls, which are implemented manually or via auto-throttle. Automatic Dependent Surveillance-Broadcast (ADS-B) and Cockpit Display of Traffic Information (CDTI) systems would be the primary enabling technologies for ATAAS. A field trial of ATAAS has been conducted in 2002 at ORD [9].

The implementation of this type of system depends upon the development of robust technology that must consider all operational issues and operate in an environment with mixed partial equipage. In addition, it must be appropriately and cost-effectively integrated into the cockpit. Finally, it would require certification by the FAA and acceptance by the aviation community that flight crew have separation responsibility during specific Instrument Flight Rules (IFR) operations.

2.3 Communication Technologies

These technologies describe upgrades in communication systems (i.e., in data transfer protocols as well as system architectures) that facilitate the flow of wake-related information between flight crew and ground personnel to implement specific future approach or departure procedures in the terminal area. These technologies may enhance potential WakeVAS technology benefits.

2.3.1 Digital Automatic Terminal Information System (D-ATIS) *Mid-Term*

This system, currently fielded by the FAA at 57 sites in the U.S., is designed to continuously provide flight crew with broadcast text messages of local weather conditions, current airport runway and taxiway status, and information on current FAA equipment outages. When used with the Terminal Weather Information for Pilots (TWIP) message service, pilots can also receive local terminal Doppler weather radar severe weather information [10].

It is envisioned that this text messaging system could ultimately be enhanced to provide wind and/or wake prognosis for improved situational awareness.[4] This enhancement would require the development and integration of an automated interface to D-ATIS with wind and/or wake prognosis instrumentation. Also, further human factors research in developing a proper HMI would be necessary to fit the required information within the display given the information bandwidth limitations of D-ATIS. It is estimated this type of application could be developed with a relatively low implementation risk, given the creation of a suitably accurate wind and/or wake prognosis.

2.3.2 Controller-Pilot Data Link Communications (CPDLC) *Mid- to Far-Term*

Designed to provide a text interface and data link between controller and pilots via digital radio, CPDLC allows standardized controller-to-pilot and pilot-to-controller communications via digital text. This reduces the need for voice communication of standard messages and clearances. Upgraded aircraft avionics with CPLDC capability are required as standard equipage in conjunction with CPDLC capable ground-air radio network. Starting on 7 October 2002 [11], this system is in initial U.S. operational use in the Miami Air Route Traffic Control Center (ARTCC) airspace for a small number of aircraft. Although there are high costs for full system implementation, many NAS benefits are anticipated from the use of this system. Some of these benefits include: a reduction in VHF spectrum congestion; increased bandwidth for aircraft communications with dispatch and other airline functions over the Aircraft Communications Addressing and Reporting System (ACARS); reduction in

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4 Note: Wake Vortex applications are not yet included and will require design and enhancement of the existing system before they are possible.

controller workload, etc. The additional development of message protocols could enable the use of CPDLC to facilitate clearances associated with candidate procedural concepts considered later in this paper.

2.3.3 Automatic Dependent Surveillance-Broadcast (ADS-B) *Mid- to Far-Term*

ADS-B is an advanced communication system that sends and receives sets of local aircraft data in real time. The primary purpose of this system is to provide air-to-air surveillance data among suitably equipped aircraft. For the purpose of implementing future wake-related procedure concepts, the ADS-B downlink (air-to-ground) portion could perhaps be defined to include selected aircraft parameters such as current aircraft weight and intended landing speed. The uplink (ground-to-air) could include the location of other aircraft in area (i.e., Traffic Information Service, Broadcast mode [TIS-B]) required for specific procedures. Requirements for wake related applications of ADS-B include the equipage of aircraft and the identification and inclusion of the required parameters in industry standards that are needed to support the specific procedural concepts requiring these parameters. Currently, extensive field trials included in FAA Safe Flight 21 are testing the basic capabilities for this technology. However, the current equipage is limited to one cargo airline and several hundred general aviation aircraft in Alaska, reducing the full understanding of system wide benefits. The risk of using ADS-B to support wake vortex procedures comes from limited or delayed equipage by carriers, and the potential lack of inclusion of the appropriate additional wake-related parameters in the industry standards for uplink and downlink messages.

2.4 Visualization Technologies

The following technologies allow for pilot/flight crew visualization of nearby hazards. These technologies may enhance WakeVAS technology benefits.

2.4.1 Cockpit Display of Traffic Information (CDTI) *Mid-Term*

The CDTI is designed to provide the flight deck a two-dimensional display of position and intent information for near-by traffic to increase pilot situational awareness. This system is required by tools that implement flight crew self-separation, as discussed in a previous section, and could be used for the display of appropriate wake vortex information with additional enhancements of display technology and data protocols. A pre-requisite capability on-board is an ADS-B system for real-time data uplink. Extensive trials of a basic CDTI capability are currently being tested in the field as part of FAA Safe Flight 21. However, the ultimate airline equipage level with this system or ADS-B is the main risk factor for realizing the potential benefits of the technology.

2.4.2 Flight Crew Wake Vortex Visualization Tools *Far-Term*

This technology is envisioned to provide a flight crew with an in-cockpit three-dimensional visualization of actual and predicted wake transport limits of an aircraft immediately in-front of or on an adjacent parallel path (e.g., through a Heads-Up Display). This technology category is typically referred to as "Synthetic Vision." NASA has conducted extensive research into the application of synthetic vision to the flight deck [12]. Synthetic vision technology and graphical displays have been field tested for aviation applications. Certification of the accuracy of actual and predicted wake transport limits would be necessary to ensure the integrity of this system. Also, incorporating the display technology and integrating it into flight crew operations is necessary for system implementation. Initial use would provide a significant increase in pilot situational awareness for visual approaches. However, any use in non-visual conditions would require FAA certification and the wide acceptance of the aviation community of flight crew responsibility for separation during an IFR approach.

2.5 Separation Monitoring and Assurance Technologies

These technologies are designed to help ensure that controllers and flight crews are maintaining required lateral and potentially vertical flight path separation during approach procedures to CSPR through real-time monitoring of approach course compliance. As such, these technologies may enhance potential WakeVAS benefits.

2.5.1 Controller Based Separation Monitoring and Assurance Tool *Far-Term*

This type of tool would allow air traffic controllers to potentially implement closer lateral spacing of independent flight paths on parallel approaches by providing flight crew earlier notice of a potential blunder of an aircraft on an adjacent path. The purpose is to provide an earlier warning of a loss of required lateral (and potentially vertical) path separation on parallel approach procedures that depend on lateral (and potentially vertical) separation minima for wake avoidance. Fast update (1 second per scan) surveillance equipment which covers the approach area (e.g., Multi-lateration, E-scan radar) is required to facilitate the implementation of this technology.

Currently, Precision Runway Monitor (PRM) with fast update radar has been certified for controller use in monitoring simultaneous approaches to parallel runways spaced less than 4300 feet apart under several different procedures [13]. PRM has been installed at MSP, PHL and STL, and is scheduled to be installed between 2003 and 2006 at SFO, JFK, CLE and ATL, for the following applications: a) straight-in instrument landing system [ILS] approaches; b) offset ILS approaches; and c) Simultaneous Offset Instrument Approaches (SOIA) [14]. For PRM or a similar tool to be applied to a wake-related application for CSPR, modifications may be required to monitor vertical separation as well as lateral separation. Also, the aviation community must accept the controller based separation-monitoring tool and new controller/flight crew procedures with specific spacing standards, for any procedure other than those already certified.

2.5.2 Flight Crew Based Separation Monitoring and Assurance Tool *Far-Term*

This technology is perhaps best exemplified by the Airborne Information for Lateral Separation (AILS), a research project conducted recently by NASA. AILS is designed to provide a flight crew with real-time guidance when a blundering aircraft on an adjacent parallel path is closer than current lateral minima for simultaneous independent parallel approaches. Thus, AILS is intended to provide the flight crew the ability to conduct independent parallel approaches with closer lateral separation than that provided under current rules, without unacceptable collision risk. This concept could perhaps also be expanded to include the monitoring of vertical as well as horizontal separation, if necessary. As an example, during an approach to CSPR with offset thresholds, a loss of vertical separation would produce a potential wake hazard. ADS-B and CDTI systems would be the primary technologies that would enable this technology. A NASA field trial of AILS was undertaken at MSP in 1999, using both auto-coupled and manually flown approaches [15, 16]. Previously, simulated approaches were flown by a set of pilot test subjects to runways with centerline separation distances of 3400 feet and 2500 feet. The primary risks of implementation of this technology for wake-related approach procedures are successfully obtaining FAA certification as well as the aviation community's acceptance of the underlying operations concept.

2.6 Navigation and Surveillance Technologies

Increasing navigation and surveillance technology capabilities may allow the implementation of increased-capacity procedures through the added precision of these next-generation systems. As such, these technologies may enhance potential WakeVAS benefits.

2.6.1 Area Navigation (RNAV) *Near-Term*

RNAV is a method of navigation that enables aircraft to fly on any desired flight path within the coverage of referenced navigation aids (NAVAIDs) or within the limits of the capability of self contained systems, or a combination of these capabilities [17]. Flight Management Systems (FMS) are used to implement RNAV operation. RNAV is a pre-requisite to Required Navigation Performance (RNP).

2.6.2 Required Navigation Performance (RNP) *Near-Term*

RNP combines RNAV operations with navigation containment and monitoring. As part of RNP, the aircraft navigation system must be able to monitor its achieved navigation performance and to determine if the operational requirement specified is not being met. A RNP-*x* capability is applied to a route, procedure or airspace that requires the aircraft to remain within ±x nautical miles laterally of the track center line. The lateral containment requirement is $2x$ or less depending on the operation. The FAA is currently developing performance requirements for longitudinal, vertical and time navigation performance as part of RNP [17].

Designed to provide FMS-based navigation using RNP reliability standards for trajectory containment, this technology would enable some wake-related procedural concepts. For example, RNP procedures could facilitate the development of offset angular approach procedures without the use of a new or relocated ILS. Other advantageous procedures, such as curved approaches, would also be facilitated. Also, RNP procedures may be used to provide containment of departure paths on CSPR. Certification standards are currently being developed by the FAA's Flight Standards division. Development of RNP arrival and departure procedures that utilize navigation equipment to be fielded in the near-term are required to implement this technology, as well as the general acceptance of the new RNP procedures. Other risks include ATC compatibility and feasibility of use.

One example of the use of RNP for terminal procedures is the RNP Parallel Approach Transition (RPAT) concept being developed by the FAA. RPAT utilizes a parallel offset RNP approach during IMC conditions to maintain the required course separation from a straight-in approach utilizing a standard ILS on the adjacent runway. The runway centerlines are spaced closer than the current limit for independent parallel approaches, 4300 feet, which motivates the use of an offset approach. The flight crew on the offset approach would accept a visual clearance after clearing the clouds, and execute an S-turn to align the aircraft with the runway centerline.

2.6.3 Precision Surveillance *Near-Term*

Precision surveillance technology can provide accurate measurements with fast-update[5] of aircraft position on the surface, on final approach and during initial climb. The Airport Surface Detection Equipment – Model X (ASDE-X) system, currently being fielded at 25 airports, is being developed initially to determine the real-time location of all aircraft and suitably equipped surface vehicles on the airport surface, with the initial focus on surface areas under FAA control. ASDE-X is a modular surface surveillance system capable of processing radar, multi-lateration and ADS-B sensor data. The ASDE-X system depicts aircraft and vehicle position and identification information overlaid on a color map of the surface movement map and arrival corridors. ASDE-X technology is being evaluated by the FAA for surveillance of the terminal airspace, specifically for coverage of the final approach corridor [18]. Field trials of ASDE-X have been conducted at DFW, MEM and Detroit

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5 Fast-Update refers to measurement technologies which update on the order of one second between measurements.

Metropolitan Wayne County Airport (DTW). The primary risk exists with the completion of certification for precision approach surveillance.

Implementation of ASDE-X technology is a prerequisite to the fielding of Runway Availability Monitoring and Prediction technology, discussed in the next paragraph.

2.6.4 Runway Availability Monitoring and Prediction *Mid- to Far-Term*

It is hypothesized that the required minimum time between arrivals could be monitored and predicted in real-time with this proposed technology based on actual runway occupancy surveillance data. The Dynamic Runway Occupancy Monitoring System (DROMS) has been developed by NASA to capture and use a database of individual arrival runway landing and exit times (collected from multi-lateration sensor data at each airport) along with surface weather, airport configuration and other related information [19]. The intent is to use this information to ultimately predict the expected maximum runway occupancy time for particular arrivals and to facilitate the reduction of in-trail separation provided when runway occupancy time is the dominant factor in the determination of in-trail separation. It may thus provide an enhancement to the capacity benefit of WakeVAS technologies where capacity is limited by runway occupancy based separation standards as well as wake turbulence based separation standards. This technology advancement depends on the successful fielding and certification of multi-lateration sensor-based surveillance systems (i.e., ASDE-X) to reliably cover the airport surface and airspace immediately around it. Field trials of DROMS are underway at MEM and DTW. DROMS currently supports historical data collection and analysis only. Actual procedural use, however, requires the development of highly reliable and stable bounds on the prediction of aircraft runway occupancy by aircraft weight class and possibly other factors (e.g., ambient surface temperature, precipitation level), in addition to the recording of actual runway occupancy.

Section 3

Potential Arrival and Departure Procedures

Many procedures for applying WakeVAS and other technologies have been identified to achieve capacity and safety benefits in a wake vortex environment. This section will summarize these procedures by organizing them into tracks of related procedures. Each track will provide an evolution of procedures as additional technologies are added. Each track begins with a baseline, and explores the additional benefits that could possibly be derived from application of WakeVAS technologies. The baseline is either the current FAA Wake Vortex program commitments, current FAA rules, or in some cases, procedures that may be possible based on current rules, but would not need the WakeVAS technologies.

The applications are described in this section in a broad-brush format in order to communicate the scope of the possibilities. A reading of the material in Appendix A is essential for a proper understanding of this potential evolution, where a more complete discussion of the procedures is included. Procedures are identified in a form such that if the FAA were to authorize them, specific detailed and targeted development would have to be undertaken for each to prove its feasibility, and the acceptability of the necessary supporting capabilities. Thus, the procedures are presented not in a technology-centered manner, but in order to highlight the type of effort that would be required by the FAA to develop, authorize and deploy them. Towards this goal, they have been ordered with an underlying qualitative assessment of an approximate order of difficulty or time frame for development and deployment.

At this stage, these procedures are simply potential concepts, to be developed later in greater detail, and assessed for potential benefits and development risks. Some of these procedures were selected this year for a more detailed benefit analysis and are described later in Section 4.

3.1 WakeVAS Technology Applications for CSPR Arrival Procedures

Closely spaced parallel runways are runways spaced from 700 to less than 2500 feet apart. The current rules dictate that under certain conditions such runways should be treated as a single runway due to the effects of wake producing aircraft. By taking advantage of runway geometry, winds, atmospheric turbulence and additional information to the cockpit, some of these rules could be relaxed and still provide the needed safety. Figure 3-1 outlines the evolution of the procedures for CSPR.

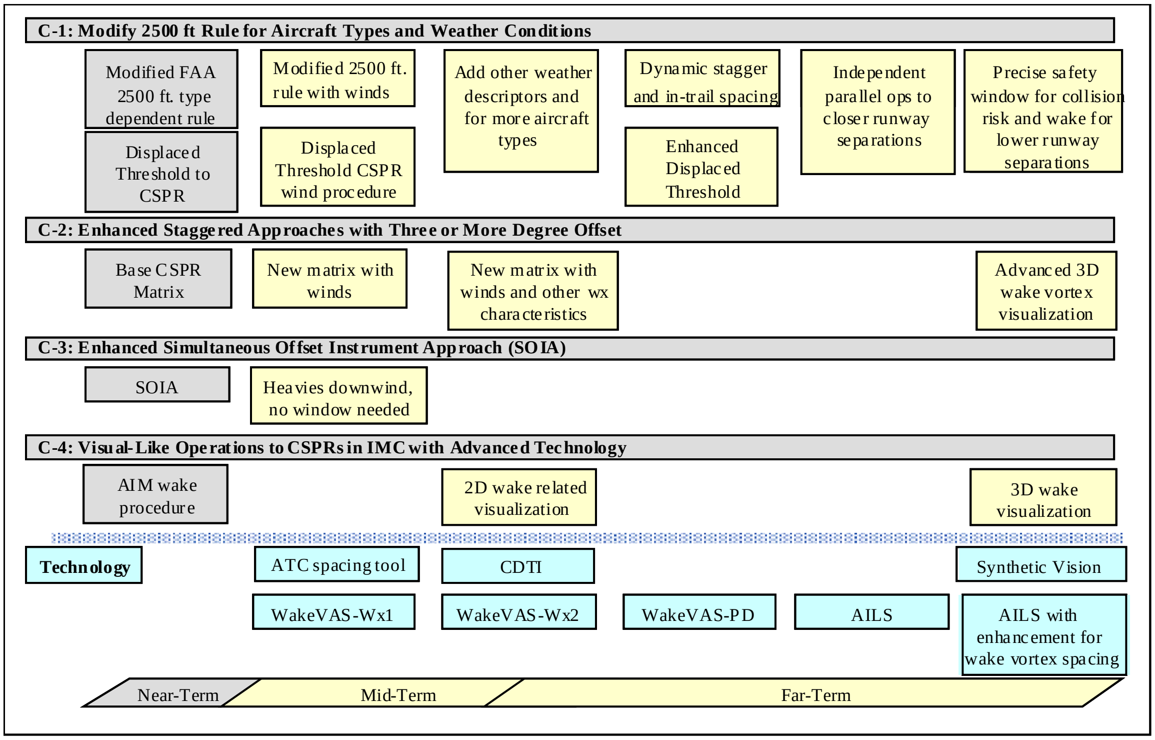


Figure 3-1. CSPR Arrival Procedures Evolution

The shaded boxes on the left represent the baselines. FAA's near-term proposal for a revised 2500 feet rule, based on the wake class of the leading aircraft, is applicable for all weather conditions [20]. The SOIA procedure is described in FAA Order 8260.49. The chart also assumes a potential three degree offset procedure, not currently authorized, as a baseline, because it could perhaps be authorized based on current rules. The technologies that are applied are shown at the bottom of the chart in an approximate order of increasing implementation difficulty or increasing implementation time-frame. These technologies were described in Section 2.

Track C-1 describes potential procedures applicable in meteorological conditions down to Category I minima. It evolves through a series of procedures that use more and more information about the wind and turbulence conditions at the airport. Under certain wind and turbulence conditions the wakes behind certain classes of aircraft either will not be transported to or will decay before reaching the other runway. When this is the case, the rules that add spacing between the aircraft for wake considerations could be relaxed. More will be said about this track in Section 4 because it was one of the tracks to be considered in more detail.

Tracks C-2 and C-3 are visual procedures, i.e., they both rely on an application of visual separation at some point during the approach. Track C-3 starts with the current SOIA rules that may utilize a window concept based on the category of the leading and following aircraft, depending on the airport geometry, and proposes the reduction or elimination of the window requirements (where applicable) based on certain wind conditions. Track C-2 starts with a potential three degree offset procedure for CSPR that would provide at least 2500 feet lateral spacing between the aircraft until the aircraft can descend and acquire each other visually. As described in Appendix A, that procedure would utilize certain separation minima depending on the type of aircraft involved, here referred to as the "base CSPR matrix." Such a procedure is not currently used in the system, but perhaps could be based on either current rules, or some basic wake vortex data. The evolution of procedures on this track proposes first to take advantage of wind conditions to reduce the separation minima in this "matrix," and later to reduce the values further to take advantage of increased dissipation of wakes with higher turbulence values or other appropriate weather conditions. Since this is essentially a visual procedure, it also postulates a very advanced evolutionary state where the visual segment may be implemented with a highly capable wake vortex visualization that may be built on a synthetic vision and CDTI platform.

The basis for the Track C-4 procedures is the wake avoidance procedure for pilots during visual operations described in the Aeronautical Information Manual (AIM). The current procedure relies on the pilot's visual observation of the aircraft generating the wake and the pilot's estimate of where that wake would exist behind the generating aircraft. The proposed evolution envisions the use of technology in conducting somewhat similar operations in less than visual conditions. It first envisages a CDTI based 2-D visualization capability that provides the pilot with a better situational awareness of own-ship with respect to the traffic to enable the conduct of visual-like operations in reduced conditions as envisioned in programs such as CDTI enhanced visual flight rules (C-EFR). It also envisions a very advanced state where visual-like operations may be conducted with advanced 3-D wake visualizations based on synthetic vision and CDTI platforms. This procedure assumes that the pilot could be given precise information on the location of the wake.

3.2 WakeVAS Technology Applications for Arrivals to a Single Runway

It has been acknowledged that the additional in-trail spacing that has been added for wake vortex considerations is conservative in many cases [21]. This evolution of procedures applies technologies that identify those conservative cases and allow the spacing to be reduced while still maintaining safety. Figure 3-2 outlines the evolution of procedures for arrivals to a single runway.

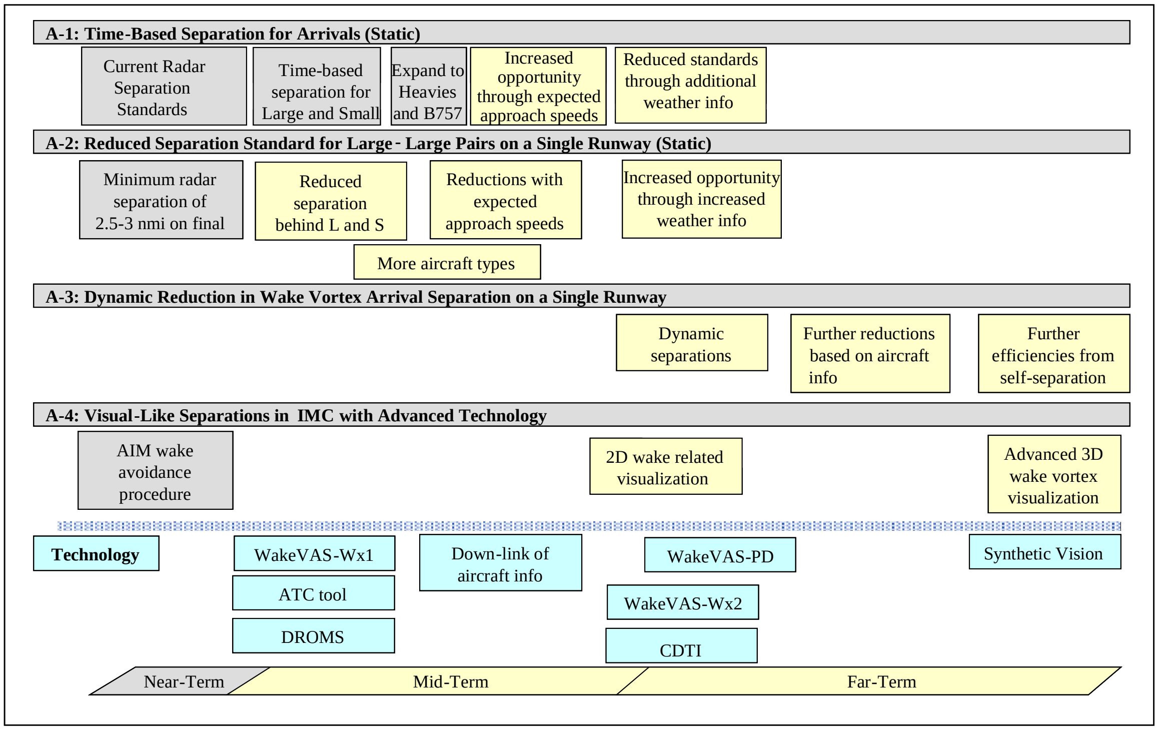


Figure 3-2. Single Runway Arrival Procedure Evolution

Track A-1 is based on the notion that there is an accepted time separation that is safe. Based on the approach speeds of Large and Small aircraft, there could be an advantage to allowing a time separation rather than a distance separation. This is explained more fully in Appendix A. Since controllers are more adept at judging distance-based rather than time-based separation between two airborne aircraft, a controller spacing tool would be needed for this track. The development of a time-based controller spacing tool would be accomplished outside the development of WakeVAS, and hence is depicted in grey. In any case, with advances in WakeVAS-Wx2, the base time-separations required for the base procedure may be reduced.

Track A-2 proposes to reduce the separation behind Small and Large aircraft under certain wind conditions to 2.0 nmi from the current 2.5 nmi (WakeVAS-Wx1). Of course, for this to work one would need to assure that the runway is clear of the preceding aircraft, hence the reference to DROMS. The application, by definition, must take into account worst possible aircraft speeds. Therefore, the domain of application may be extended to conditions that may not otherwise facilitate such reductions, by downlinking expected approach speeds. Taking account of turbulence information should expand the opportunities even further since certain turbulence conditions may dissipate wakes faster. The WakeVAS-Wx2 technologies would provide a means for identifying those conditions.

Track A-3 picks up where Tracks A-1 and A-2 leave off. Using the WakeVAS weather information and active wake detection and prediction, a dynamic determination of the minimum safe wake vortex spacing for each pair of aircraft could be made. It would include reduced separations behind all types of aircraft. Although simpler solutions with fixed separation reductions may be possible, simple spacing aids could facilitate a greater range of separation values, and hence greater opportunity. With a long enough and stable enough prediction and such controller automation the controllers could take advantage of reduced separations.

Track A-4 is analogous to Track C-4. It starts from the procedure that the pilots use from the AIM where the pilot estimates where the wake would exist behind the preceding aircraft and flies accordingly. The proposed evolution first envisages a CDTI based 2-D visualization capability that provides the pilot with a better situational awareness of own-ship with respect to the traffic he is following, to enable the conduct of visual-like operations in reduced conditions as envisioned in programs such as C-EFR. Finally, as in track C-4, it envisions a very advanced state where visual like operations may be conducted with advanced 3-D wake visualizations based on synthetic vision and CDTI platforms.

3.3 WakeVAS Technology Applications for Departures, Intersecting Runways and Mixed Arrivals and Departures

This set of procedures explores operations involving departures from single runway, CSPR and intersecting runways. Situation where runways are dedicated to departures as well as mixed arrival/departure operations are considered. Figure 3-3 outlines the evolution of these procedures.

It should be noted that wake turbulence restrictions for departures are enforced in all meteorological conditions: VMC as well as IMC. Track D-1 addresses departures from CSPR. It starts with the FAA mid-term proposal that for certain wind conditions wakes from departure off the downwind CSPR would not reach the upwind CSPR, thus allowing the upwind runway departures to be released without adding additional wake vortex separation. The benefits to be gathered from such a procedure are the greatest when aircraft can be fanned or launched on diverging headings. The procedure, of course, must account for the entire envelope of aircraft performance values to assure safety. There may be room for improving the procedure in those cases where aircraft can provide a more reliable ground track during departure, such as that realized by precision RNP based departure procedures. Track D-1 then evolves through procedures that use additional weather information such as turbulence information that can identify conditions when aircraft can be released earlier without risking a wake interaction, and finally to dynamic separations with a mature WakeVAS system that uses active prediction and sensing to reduce the system buffers used in earlier stages.

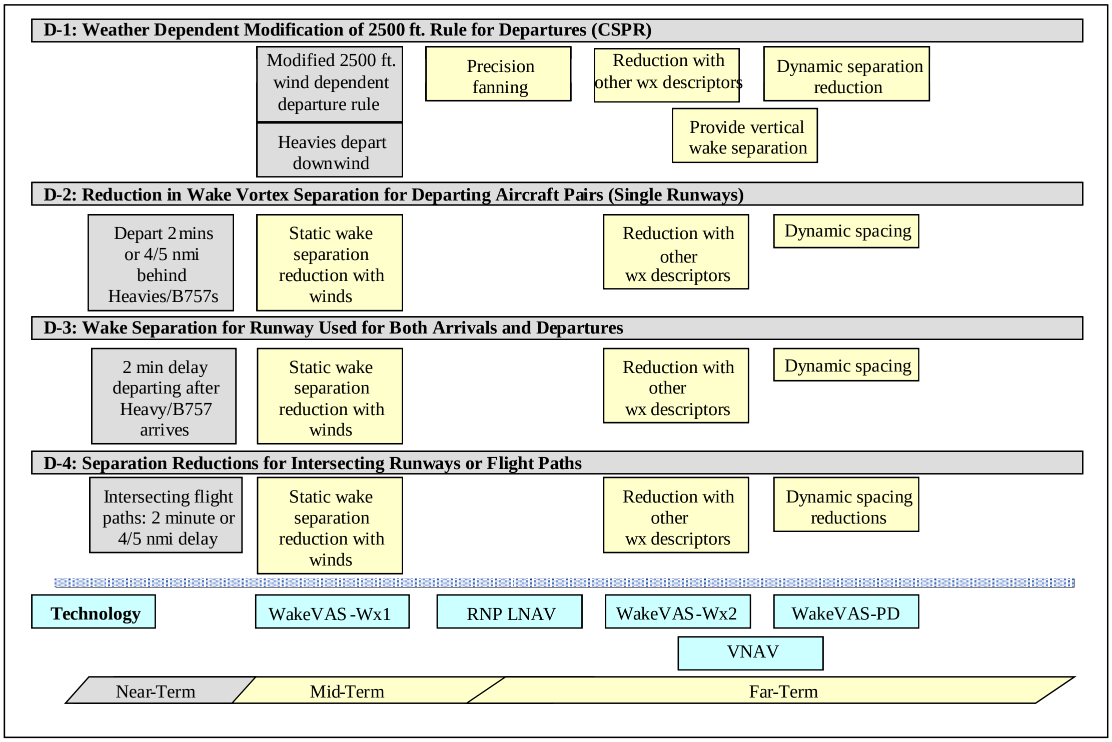


Figure 3-3. Departure, Intersecting and Arrival/Departure Procedures Evolution

Track D-2 extends the application to single runways. It proposes that the two minute (or 4/5 nmi) separation behind Heavy and B757 aircraft be reduced based on certain wind conditions that transport the wake out of the path of the next departing aircraft. This would be followed by the addition of technology to measure and develop prognosis of the turbulence levels which would enable further reductions such that the wake would decay before the next departure entered the area. Eventually, with the mature WakeVAS system, the environmental information could be used to tailor the departure separation between each pair of departing aircraft more tightly.

Track D-3 starts with the current rules for runways used for both arrival and departures which state that the soonest a departing aircraft can begin its takeoff roll is either after the previous arrival clears the runway or two minutes after a B757 or Heavy aircraft lands. The evolution of this set of procedures makes use of WakeVAS technologies to determine if the wake from the preceding Heavy or B757 arrival has cleared the path of the succeeding departure by either transport or decay. In the far term the procedure can be enhanced as in Track D-2 with turbulence based prognosis, and eventually with a mature WakeVAS system predictions using active wake predictions and sensing.

Track D-4 considers reduced separation for intersecting runways or flight paths. Wake vortex encounters are most dangerous when aircraft are in-trail (i.e., in an axial encounter) since the following aircraft can be subjected to large rolling moments for several seconds. Transverse encounters experience different dynamics. However, separation standards for transverse geometries are the same as for axial geometries. This track will determine when the wake at the intersection is no longer a factor for the following aircraft. With the succession of additional technologies, more precise determinations can be made about the transport and/or decay of the wake at the intersection allowing the controller to reduce the separation between the aircraft.

3.4 Safety Related and Other WakeVAS Technology Procedures

The remaining procedures are safety related or otherwise do not naturally fall under the categorization discussed above. These will be summarized below.

3.4.1 Wake-related Advisories for Visual Operations

It is the stated policy of the IFALPA that wake vortex visualization capabilities be developed [6]. The U.S. Air Line Pilots Association (ALPA) endorses this policy. This procedure evolution proposes to define cockpit visualization capabilities. It is proposed that the information driving this visualization be provided by ground based sensors, data fusion and communications. As additional technologies are applied, the visualization can get more precise and give the pilot a better opportunity to fly where there are no wakes.

The wind information from ITWS can be customized to provide flight path specific winds (headwind and crosswinds) instead of the grid of wind information currently given in meteorological coordinates. This procedure will broadcast ITWS wind information for the terminal area to pilots to be provided in the cockpit. The pilots would use their training to judge the flight path necessary to clear the wake based on the winds.

Once active detection of wakes is available from WakeVAS in the far-term, the wind advisory service could be upgraded to provide wake advisories based on individual aircraft wakes and aircraft positions on the final approach path. These wake advisories could be displayed to the pilot on a CDTI or other display showing a volume of airspace to avoid.

3.4.2 Wake Avoidance at Glideslope Intercept

One region where pilots have informally reported encountering wakes is in the vicinity of glideslope intercept while executing an approach. The authors are not aware of any extensive wake data collection efforts in this region (from 4 to 11 nmi out on final). Further documentation of the conditions surrounding these wake encounters would help researchers to understand the potential causes and would suggest ways to modify current operations to reduce their occurrence. WakeVAS algorithms could be used to predict the location and strength of wakes from aircraft in simulated scenarios and analysis tools could detect when trailing or crossing aircraft might encounter wakes of significant intensity.

3.4.3 Aircraft Wake Vortex Categorization

Aircraft are currently categorized with respect to their wake vortex characteristics based simply on their gross take off weight. Although aircraft wake generation certainly depends on aircraft weight, there are other significant factors such as wing span and airspeed of the leader and follower and roll susceptibility of the follower that also directly affect both wake generation, susceptibility and controllability with respect to wakes. Research indicates that the current categorization can not be considered to provide a uniform level of safety with respect to wake encounter [22, 23]. Considerable room appears to exist in refining the method of classification of aircraft into wake-related categories so that a more rational and more uniform safety basis may be provided. This may require the use of controller spacing tools if the resulting classification becomes significantly more complex than the current wake categorization.

3.4.4 Heavy/B757 Passing Procedure

Currently, controllers are responsible to determine that during visual approaches to closely spaced parallel runways, a Heavy or B757 aircraft will not pass another aircraft, and a Large will not pass a Small aircraft. This restriction is to protect the smaller aircraft from the wake of the larger aircraft after it is passed. Ensuring that aircraft passing will not occur increases the workload of the final approach controller. This procedure will establish conditions when this rule can be suspended when the Heavy or Large is on a particular runway, or perhaps set some limits to how much the Heavy aircraft could pass. (e.g., pass the leading aircraft by no more than one nmi), based on a reliable current prediction of winds along the approach path.

Section 4

A Subset of Procedures for Further Analysis

Section 3 summarized many different procedures and enhancements that could apply WakeVAS and other potential technologies. It was the stated purpose of this task to provide a benefit analysis of promising alternatives to enable a comparison between them. The resources available for this effort were not sufficient to evaluate all possible options, so it was necessary to select a subset of procedures for more detailed analysis. The following aspects were considered in selecting this subset:

- Provide a step-wise evolution from current and proposed FAA wake vortex procedures to procedures that take advantage of mature WakeVAS technologies.
- Select procedures such that assumptions regarding incremental benefits can be traced quantitatively to specific WakeVAS technology and knowledge.
- Procedures selected should represent arrivals and departures from single runways as well as CSPR.
- One of the procedure tracks should analyze multiple incremental steps, starting with the current or proposed FAA procedure and ending with a procedure that requires a mature WakeVAS system. The remaining procedure tracks selected should just be analyzed for the mature WakeVAS state.

In discussions with NASA project management, it was agreed that the CSPR arrival procedure (C-1) would receive the most detailed analysis and that multiple incremental steps would be simulated, culminating with a procedure using a mature WakeVAS system. Capacity and benefit analysis would be performed on each incremental step to discover which applications of WakeVAS related technology provided the most significant capacity gains. It was also agreed that a final procedure step using a mature WakeVAS system (represented by WakeVAS-PD in Section 3) would be analyzed and simulated for single runway arrivals (A-3), CSPR departures (D-1), and single runway departures (D-2). Figures 4-1 and 4-2 show the procedure tracks, and steps within each track, that were analyzed and simulated.

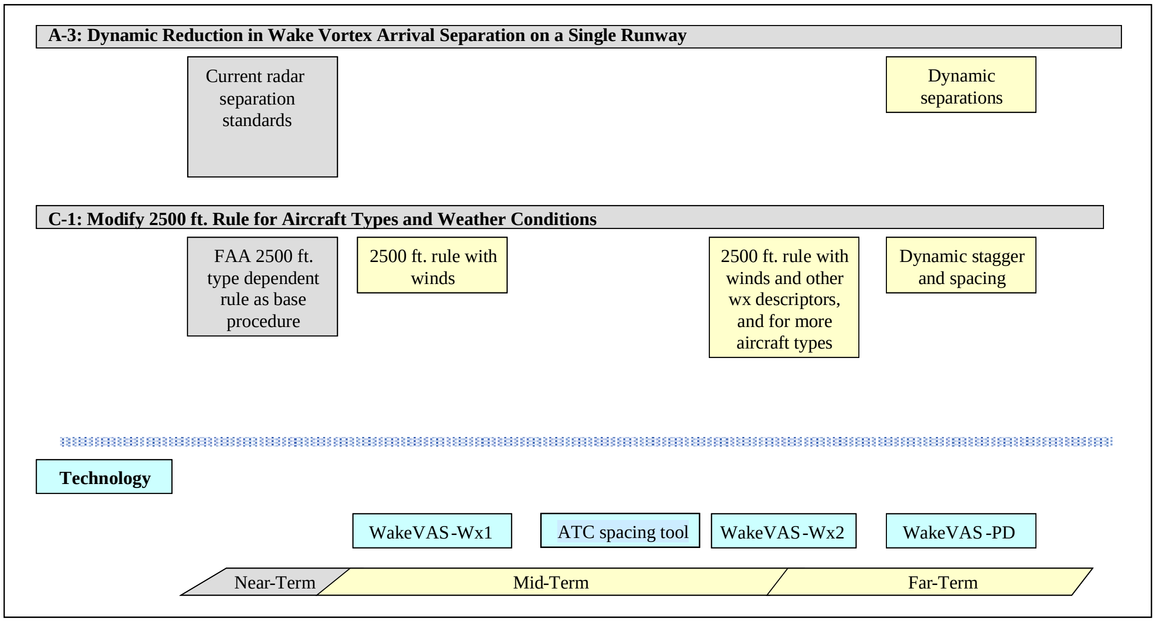


Figure 4-1. Arrival Procedures Selected for Further Analysis

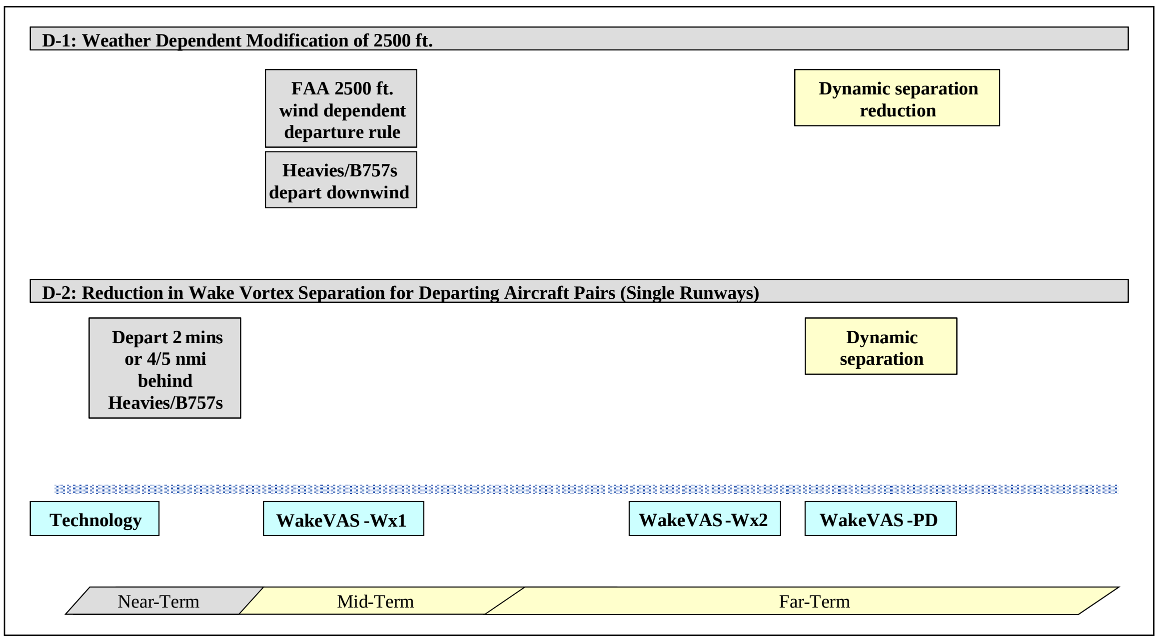


Figure 4-2. Departure Procedures Selected for Further Analysis

The options are arranged into tracks showing an incremental evolution of a particular procedure as various technologies mature and can be applied to achieve some level of additional benefit in each step. Each track begins where the current FAA wake program (or existing FAA rules) leave off and explores additional operational benefits that could possibly be derived from application of WakeVAS technologies. The starting point for single runway arrival and departure procedures is the current rules in FAA Order 7110.65. For arrivals to CSPR, the base procedure is the FAA near-term proposal for a revised 2500 feet rule based on the wake class of lead aircraft, applicable for all weather conditions down to Category I. For departures from CSPR, the base procedure is the FAA mid-term proposal for a revised 2500 feet rule based on winds.

4.1 Track A-3: Dynamic Reduction in Wake Vortex Arrival Separation on a Single Runway

The base procedure for track A-3 is the current FAA rules for minimum radar and wake turbulence separations. These include 2.5 nmi between aircraft established on the final approach course within 10 nmi of the landing runway when a Small aircraft is leading with any weight class aircraft following or a Large aircraft is leading and a Large or Heavy aircraft is following. (An average runway occupancy time of 50 seconds or less must be documented for the arrival runway. If these conditions are not met, then the minimum radar separation is 3.0 nmi.) Wake vortex separation requirements increase this to 4 to 5 nmi on final and to 4, 5, or 6 nmi when crossing the landing threshold. Table 4-1 summarizes the in-trail separation requirements for arrivals to a single runway.

Table 4-1. Distance Separation (nmi) Required between Aircraft Landing on the Same Runway

		Leading Aircraft			
		Small	**Large**	**B757**	**Heavy**
Trailing Aircraft	**Small**	2.5/3	4	5	6
	Large	2.5/3	2.5/3	4	5
	B757	2.5/3	2.5/3	4	5
	Heavy	2.5/3	2.5/3	4	4

The determination of dynamic spacing intervals for arrivals is through the use of WakeVAS weather information and active wake detection and prediction. These capabilities will enable dynamic determination of minimum safe wake vortex spacings for each trailing aircraft on final approach. Rather than being based only on historical wake observations, this enhancement will incorporate prediction of wake decay, sink and transport based on WakeVAS weather sensors and the AVOSS prediction algorithm. The wake behavior predicted by WakeVAS will be constantly checked for accuracy through the use of ground-based active wake detection sensors. If the measured wake location or strength is trending away from the predicted wake values in the direction of greater wake hazard, then a transition out of this procedure would be initiated. The bound on the difference between the predicted and actual wake behavior must be sufficiently small that it will allow time for aircraft already on approach to complete their approach before the procedure would need to be discontinued for safety reasons.

Dynamic changes in predicted safe separations would require decision support tools for controllers so that the projected separation adjustments are used effectively and so that these changes are largely transparent to controllers. Spacing tools will certainly be required for the final controller. Tools may also be required for a traffic manager position, if one exists, and for the feeder controllers so that traffic being delivered to the final controller reflects appropriate responses to the changes in separation values.

For the latter function, the active wake detection and prediction system could provide approach control with the current dynamic separation standards in effect for each pair of aircraft types for the appropriate look-ahead time. This may help the traffic manager and feeder controllers plan the traffic feed to the final controllers. It may also help final controllers establish the desired sequence on final approach with the knowledge of the current minimum separation factors for each pair of weight classes. Additional decision support tools may be needed for properly accomplishing these functions.

To implement dynamic separations for each trailing aircraft on final approach a controller tool, such as the ghosting tool that is used for the CRDA, would need to be implemented. WakeVAS would provide the separation values for each trailing aircraft based on the wake behavior predicted for its lead aircraft. These separation values could then be used by the ghosting tool to present a ghost target on final at the target spacing for each aircraft. In addition to capacity gains enabled through reduced in-trail separation, the more accurate spacing of aircraft using the ATC tool may provide addition gains through a reduction in the variability of spacing actually achieved on final.

This ghosting tool would have a similar Computer Human Interface (CHI) to the current CRDA; however it will also have an interface to the active wake prediction and detection system in order to generate target ghosts at the required separation values. Figure 4-3 shows a depiction of such a ghosting tool.

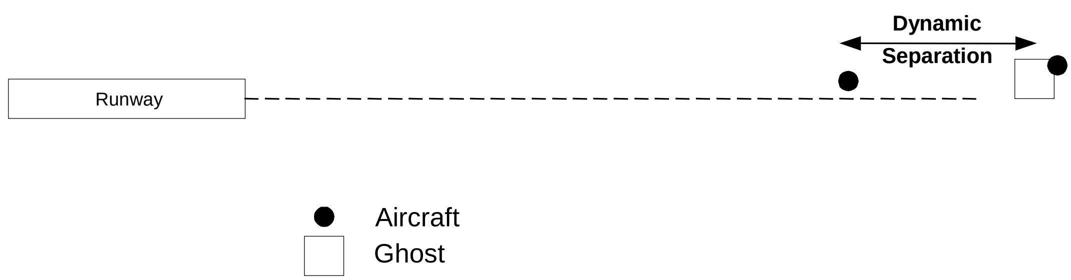


Figure 4-3. Depiction of Ghosting Tool for Dynamic Spacing on Single Runway Approaches

The active wake prediction subsystem would need to provide a highly reliable forecast of maximum wake persistence in the approach path for each pair of equipment weight classes. This forecast would need to be available 10-15 minutes prior to landing so that each flight could be established on its approach with the appropriate dynamic spacing, representing the minimum safe separation from the preceding aircraft during the period of the approach. The dynamic separation standard should not normally be adjusted while the flight is on the approach. Consideration of differences in the minimum spacing for wake vortex avoidance required on the downwind, turn and final approach legs would also have to be included in the controller ghosting tool used to implement the procedure. Finally, provision would have to be made for specifying the sequence in a simple manner so that the target ghost can be generated appropriately. This may imply additional workload for controllers, and it would have to be determined through simulations whether the additional workload is acceptable. The CHI in Standard Terminal Automation Replacement System (STARS) may make this easier to accomplish.

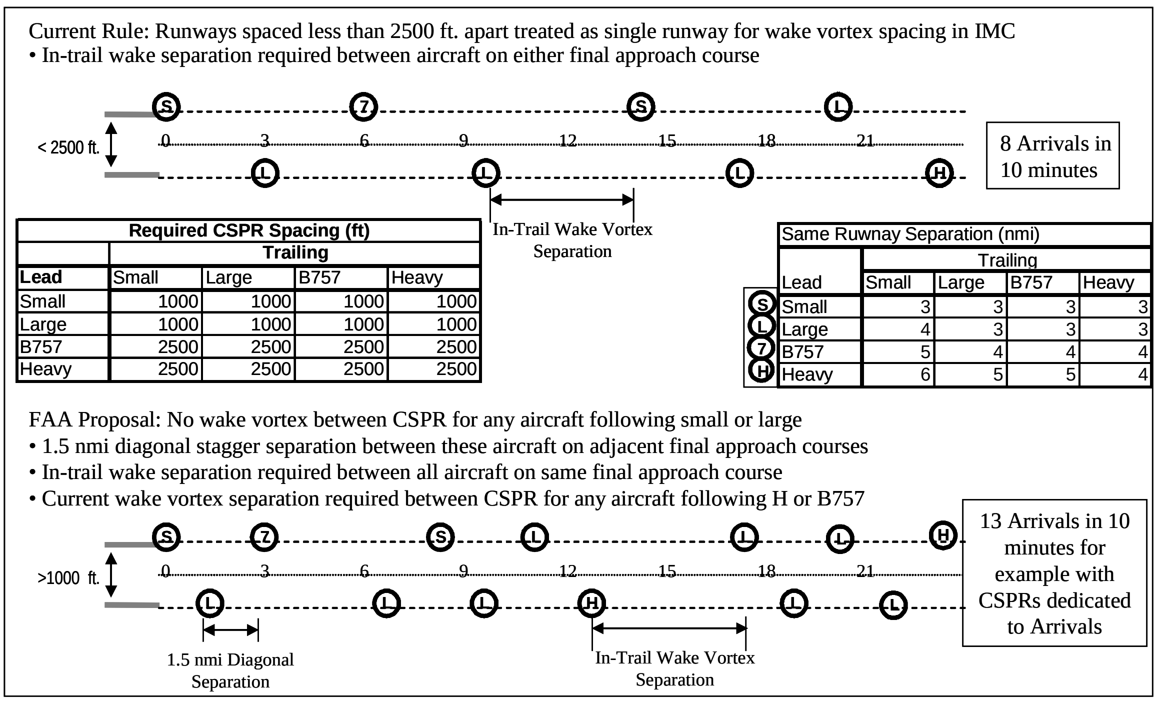
The active wake detection subsystem is essential to provide real-time feedback of each aircraft's observed wake to the prediction subsystem. This would provide real-time quality control measurement on the current separation standard, and facilitate the required safety net. This information would be used to update the current dynamic separation standard as required, and would have to be reflected in the target ghosting positions if it reflects an increase in the safe spacing value. For stability, reductions in minimum safe spacing would not be indicated to targets already being provided ghost targets[6]. Indications (i.e., alerting) that a change has occurred would also have to be provided to the approach controller, if the wake prediction increases the required separation for targets already being spaced on final. Such changes will not normally be desirable and the design must minimize them. In extreme

6 Since the spacing already being provided would exceed the new minimum.

cases, such a sudden increase in separation standard may require vectoring of flights on the approach or even a go-around of the next flight to land, but the system should be designed so that such extreme measures are very unlikely.

4.2 Track C-1: Modify 2500 feet Rule for Aircraft Types and Weather Conditions

The base procedure for track C-1 is the proposed FAA near-term modification of the 2500 feet minimum lateral spacing rule for wake vortex dependency for arrivals to CSPR. For this procedure (see Figure 4-4) runways with at least 1000 feet parallel runway spacing would not be considered CSPR for an aircraft pair when Small or Large wake class aircraft are leading. All other arrival cases would require the current 2500 feet lateral runway spacing to not be considered CSPR.



Required CSPR Spacing (ft)				
	Trailing			
Lead	Small	Large	B757	Heavy
Small	1000	1000	1000	1000
Large	1000	1000	1000	1000
B757	2500	2500	2500	2500
Heavy	2500	2500	2500	2500

Same Ruwnay Separation (nmi)				
	Trailing			
Lead	Small	Large	B757	Heavy
S Small	3	3	3	3
L Large	4	3	3	3
7 B757	5	4	4	4
H Heavy	6	5	5	4

Figure 4-4. FAA Proposed Near-Term Procedure

A generic evolution is first described, followed by a more detailed specific evolution.

The first generic step in the evolution in Track C-1 could use WakeVAS wind information in the mid-term timeframe to determine when wakes will be transported clear of the CSPR. The upwind and downwind runways are considered separately for each wind case and lead aircraft wake class. Data will be collected over an extended time period documenting when each wind condition reliably transports the wake of certain class aircraft such that the wake is no factor for arrivals to the parallel runway. This historical data can then be used to establish an arrival procedure that can eliminate wake dependencies when appropriate. Although displaced thresholds could probably be used to advantage to provide vertical separation between aircraft approach paths, that option was not analyzed for this study because no data was available in that domain at the time of this work. This step may be restricted to certain aircraft types (e.g., Large or Small aircraft leading) in order to facilitate early certification.

The approach region that needs to be protected from wakes generated by aircraft approaching a parallel runway needs to be defined. This region would extend from the touchdown point on the runway out the final approach course. Wake encounters near the ground are the most serious from a safety perspective, so this region would certainly need to include the runway threshold and potentially out to the point of glideslope intercept (7 nmi or further out, depending on the airport arrival operation). The width of the region would vary based on the flight technical error of aircraft using the approach plus a safety buffer. The WakeVAS program has designed an approach volume that has been used for single runway arrivals [5]. This approach volume could be adapted to apply to CSPR arrivals as well.

Wind data currently collected at airports is primarily for winds at the surface. Wind measurements at various distances and heights along the final approach corridor will be required to accurately determine which case from a statistical database of wake transport behavior is applicable for the current winds.

The second generic stage could be to include WakeVAS turbulence and other weather descriptors in the mid to far-term to determine cases when wakes will decay and not be a factor to aircraft approaching the parallel runway. The knowledge of EDR and other weather factors and their effect on the time for a wake to decay to background turbulence level, combined with the knowledge of wake transport behavior, may provide other opportunities to safely lower runway spacing requirements. As more data and operational experience accrues, more combinations of lead and trail aircraft type (e.g., Heavy leading) may be included in this stage.

A statistical database of wake decay and transport behavior would need to be developed to support this capability. Sensors to detect wakes and associated wind and other weather conditions would need to be used to collect data from various points along the final approach for a large number of arrivals representing all aircraft types and a full range of weather conditions. A data collection effort such as this has been started at STL [24].

In the far-term, active wake prediction and detection may enable the third generic stage to allow dynamic stagger and dynamic in-trail spacing values as well as opportunities to use CSPR with less displacement between their runway thresholds, if a threshold stagger dependence has been executed in preceding versions of this procedure. This enhancement would include the establishment of a new reduced standard for dependent parallel operations (possibly less than 1.5 nmi stagger in IMC) for runways spaced closer than 2500 feet.

This stage would determine dynamic spacing intervals for arrivals using WakeVAS weather information and active wake detection and prediction. In contrast, the previous stage used a statistical database derived from a large number of wake observations to determine the transport limits for wakes from various aircraft under specific weather conditions. This database could still serve to calibrate the wake prediction model in this stage.

NASA Langley is currently analyzing weather data (wind and atmospheric turbulence) to determine if a predictable relationship can be established between wind intensity and atmospheric turbulence. Turbulence can have a dramatic effect on the decay rate of wake vortices, but there are currently few sensors at any airports that measure information such as EDR. If a reliable relationship can be established between wind speed and turbulence, the prediction of wake vortex decay and the distance a wake is transported prior to decaying to the level of background turbulence could be predicted more accurately using airport weather observation systems that provide wind information but not atmospheric turbulence information.

The wake behavior predicted by WakeVAS will be constantly checked for accuracy through the use of ground-based active wake detection sensors. If the measured wake location or strength is trending away from the predicted wake values in the direction of greater wake hazard, then a transition out of this procedure would be initiated. The bound on the difference between the predicted and actual wake behavior must be sufficiently small that it will allow time for aircraft already on approach to complete their approach before the procedure would need to be discontinued for safety reasons. For additional discussion of the use of active wake detection and prediction, please see the related discussion as it applies to single runway arrivals in Section 4.1.

The potential procedures in this track could provide benefit during marginal VMC and IMC weather conditions.

A more detailed evolution was developed based on these generic steps, as follows:

Incremental Step	**Relation to AVOSS Output**	**Notes on Program Maturity and WakeVAS Stage**	**Evolutionary Procedure Steps for More Detailed Analysis**[7]
a	Use crosswinds to allow wake independence of *upwind* runway behind *Large* aircraft; Judge wake transport of leading wake category aircraft at the 70 m^2/s level, add safety buffer to minimum crosswind required	WakeVAS-Wx1	
b	Use crosswind to allow wake independence of upwind runway, adding a safety buffer to minimum crosswind required	WakeVAS-Wx1	1
c	Use crosswind to allow wake independence for both runways if the wind is low enough, judging the wake transport of leading wake **category** aircraft at the 70 m^2/s level, adding a safety buffer to minimum crosswind required	WakeVAS-Wx1	2
d	Use crosswind to allow wake independence for both runways if the crosswind is low enough, judging wake transport of leading **cluster** aircraft at the 70 m^2/s level, adding a safety buffer to minimum crosswind required	Uses controller spacing tool	3
e	Reduce minimum separations between aircraft on parallel approaches to 1 nmi, adding a safety buffer to the minimum crosswind required	Uses RNP based approaches	

7 The steps in this column correspond to those in Table 5-3.

Incremental Step	Relation to AVOSS Output	Notes on Program Maturity and WakeVAS Stage	Evolutionary Procedure Steps for More Detailed Analysis[7]
f	Use crosswind to allow wake independence for both runways if the wind is low enough with the addition of turbulence considerations, adding a safety buffer to the minimum crosswind required	WakeVAS-Wx2	
g	Use crosswind to allow wake independence for both runways if the crosswind is low enough, judging wake transport of leading **cluster** aircraft at a level dependent on the weight class of the trailing aircraft, adding a safety buffer to minimum crosswind required	Uses hazard level refinements	4
h	a. Judge wake transport of leading cluster aircraft at the 70 m^2/s level, without adding a safety buffer to the minimum crosswind required	WakeVAS-PD	
	b. Use crosswind to allow wake independence for both runways if the crosswind is low enough, judging wake transport of leading **cluster** aircraft at a level dependent on the weight class of the trailing aircraft, without adding a safety buffer to the minimum crosswind required	WakeVAS-PD with hazard level refinement	5

The steps are presented in order of increasing complexity and/or dependence on advanced technology. Only the steps listed in the right-most column in the table were finally selected for a more detailed benefit analysis, reported separately. Step a takes advantage WakeVAS wind information to determine when wakes of Large (or Small) aircraft approaching a downwind runway will transport clear of the upwind approach. When the wake decays to 70 m^2/s it is judged to be at a background turbulence level and no longer a threat to any aircraft. A 5 kt buffer is added to the required wind to accommodate uncertainty in the wake transport. Step b extends the procedure to remove wake separation behind any wake category (Small, Large, B757, Heavy) leaders on the downwind runway for trailing aircraft approaching the upwind runway. Step c extends the procedure to include leaders on either runway under certain wind conditions when their wakes will transport clear of the parallel approach.

Step d, using crosswind to allow wake independence for both runways if the wind is low enough, is described in detail in Section 6. A preliminary quantitative analysis of this step showed that it can capture a significant portion of the benefit of this track, and was therefore chosen as the subject of the concept of use described in that section. This step also includes a feature where aircraft types are assigned to a new set of eight aircraft clusters (versus the current four weight classes) for the determination of wake intensity and lateral transport. The definition and use of aircraft clusters is discussed further in Section 5.2.1. The use of a controller tool is required to indicate whether wake separation needs to be provided between an aircraft and a trailing aircraft approaching a parallel runway. Aspects of this tool and the supporting system architecture are presented in Section 6.

Step e uses RNP based technology to reduce the minimum stagger between aircraft on parallel approaches to 1 nmi from the 1.5 nmi currently in use. Preliminary collision risk analyses indicate that such reduction may be possible if navigation and pilotage issues can be addressed. RNP based offset approaches would be used to minimize the adverse effects of such navigation and pilot errors on the procedure. Step f adds the consideration of atmospheric turbulence and its effect on wake decay.

Step g introduces the concept of certain aircraft types being more subject than others to roll events when encountering a wake vortex [32]. For simulation purposes the existing wake categories were used to judge the sensitivity to wakes. Other factors, such as whether the engine mass is located on the wings or on the fuselage, can also contribute to an aircraft's roll reaction when encountering a wake vortex. For all the steps a-g, a 5 kt safety wind buffer is added to account for uncertainty in the wake transport. Of course the size of such a buffer must be determined through further research.

Step h introduces WakeVAS real-time prediction and detection of wakes. This enables the removal or reduction of the safety wind buffer and increases the opportunities for gaining benefit from the procedure. Step h has two increments. The first increment requires the wake to decay to background turbulence level before considering it as no hazard to the trailing aircraft approaching the parallel runway. The second increment uses the variable wake hazard levels introduced in Step g.

All of the steps in this evolution maintain current in-trail wake separation requirements for aircraft approaching the same runway. Only wake separations between a lead aircraft and a trailing aircraft approaching the parallel CSPR are impacted.[8]

4.3 Track D-1: Weather Dependent Modification of 2500 feet Rule for Departures (CSPR)

The base procedure for Track D-1 is the FAA proposed mid-term procedure for wind-dependent CSPR spacing for departures (Figure 4-5). Currently, wake turbulence separations are applied for departures in *all* meteorological conditions: IMC as well as VMC. For certain crosswind conditions, wakes from departures off a downwind runway transport with the wind and would not reach the upwind departure runway. Departures from the upwind runway do not require wake separation from a previous departure off the downwind runway for this procedure. In-trail separation requirements between aircraft departing from the same runway are not affected. An additional operational benefit to this procedure is that no departure delay would be incurred by an intersection departure from the upwind runway. Currently, a three minute delay is required for intersection departures for some aircraft pairs. If operationally feasible at a particular airport, additional capacity can be gained by restricting departing Heavy aircraft to the downwind runway.

The mature WakeVAS state in Track D-1 would use WakeVAS predicted wake decay and transport information to determine dynamic spacing intervals between each pair of departures. WakeVAS would include sensors to measure wind, turbulence, and other weather factors and would use validated algorithms to predict the wake behavior of each departure based on parameters for the aircraft type (e.g., wing span, maximum takeoff weight, minimum takeoff speed, takeoff configuration). WakeVAS would also use active detection of wake position and intensity to continually monitor the performance of the wake prediction system. The mature WakeVAS system will define departure corridors for each aircraft and predict when the wake of the leading departure would be clear of the path for the trailing departure.

8 Combining the benefits of CSPR and single runway approach procedures are described in Appendix A.

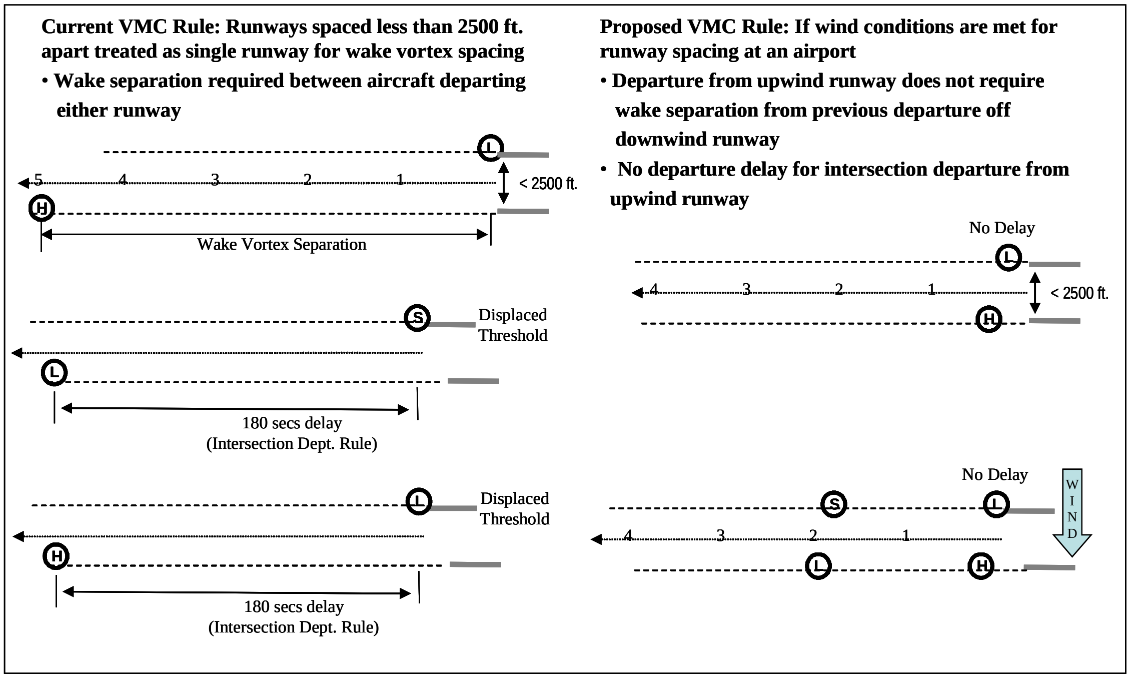


Figure 4-5. FAA Proposed Mid-Term Procedure

The definition of a departure corridor can be very difficult and is very dependent on specific airport operations and noise abatement procedures. A region that encompasses the horizontal and vertical paths of all departures can result in the corridor representing a large region of airspace. This of course depends upon how far out from the departure threshold it is necessary to extend this region of wake protection. This region would begin at the earliest point at which aircraft become airborne when departing a runway and would extend out to a distance and height that would be determined based on the departure geometry. If an airport is employing the ATC rule that allows an IMC separation of 1 nmi when aircraft are immediately turned to diverging courses (see departure rules in Appendix B), then the lateral extent of the departure corridor would be much greater than the case where departures maintain runway heading for their initial climb. On the other hand, in the latter case, the corridor would extend a farther distance along the departure path to a higher altitude to cover the region of the common paths. The climb trajectory of an aircraft can also vary greatly depending on the specific aircraft capability, loading, density altitude, headwind, noise abatement rules, and company policy.

One technology option for increasing the certainty in vertical and lateral paths is to use RNP Lateral Navigation (LNAV) and Vertical Navigation (VNAV) paths to limit the dimensions of the departure corridors. If this technology were used for all departures, the area where wake prediction and detection would need to be accomplished could potentially be much smaller. A step toward this capability may be to determine the approximate heading an aircraft will fly when departing based on the departure fix in that aircraft's route of flight. Knowledge of airport specific departure practices could also help in designing wake avoidance procedures most suited to those airports. In some cases, it may be possible to restrict the procedure to cases when departures are alternated to different departure fixes so that the resulting consecutive departures are assigned diverging courses; in such cases, the area that would need to be monitored for wakes could be as little as beginning at the takeoff point and extending into the initial turn towards the departure fix. This region is close to the ground and close to the runway complex at the airport, facilitating placement of wake and weather sensors. Of course, if a departure does not fit this pattern of diverging courses, then standard wake separation would need to be applied. LNAV and RNAV paths may also be used to reduce required separation, as explained in the next section.

An option for using WakeVAS in an application with CSPR departures would be to only consider wake decay time versus wake transport or sink. Departure intervals would be determined by the time it would take for the wake of the previous departure (off either CSPR) to decay to the level of background turbulence. This would remove the need for a departure region to be defined and the associated operational complexities. Depending on a specific aircraft's wake intensity and decay characteristics and whether the atmospheric turbulence levels accelerate or delay wake decay to the background turbulence level, the use of decay time only may or may not result in a significant operational benefit (e.g., increase in departure rate). Which technology option the mature WakeVAS technology will use will depend on the relative benefits and development risks of the various options.

An appropriate controller interface will be required to enable the implementation of the dynamic spacing values envisaged in this concept. The determination of wake decay time could be based on individual aircraft, the weight class of an aircraft, or categorizing aircraft into wake clusters, similar to the approach described in Section 4.2. If the resulting departure delay were based on the weight class of the previous departure, then a simple modification to current wake procedure (e.g., 90 second delay versus two minute delay after a Heavy/B757) might be possible. If the departure delay were dependent on the wake cluster or the individual aircraft type of the previous departure, then a controller tool would be required to provide indications to the controller in an operationally acceptable manner.

4.4 Track D-2: Reduction in Wake Vortex Separation for Departing Aircraft Pairs (Single Runways)

The base procedure for this track is the current departure rule calling for 2 minutes or 4 or 5 nmi behind B757s or Heavy aircraft.

The mature WakeVAS system for departures from single runways will use active wake prediction and detection to enable dynamic wake separation values to be determined for each departure. Departures may go out on a common track or may be fanned after takeoff. The system will consider the common path segments to predict potential reductions, as well as predict the reduced spacing necessary if the trailing aircraft is fanned to an initial heading different from the preceding flight immediately after takeoff. This is because the airspace volume over which the wind and wake behavior must be predicted is in this case much smaller than the volume encompassing entire departure path of a flight. See Section 4.3 for a more detailed discussion of factors related to defining wake protected regions for departures. That section discusses the complexities of defining departure regions. As discussed there, a simpler capability basing departure separation on wake decay time only could also be implemented. The determination of wake decay time could be based on individual aircraft, the weight class of an aircraft, or categorizing aircraft into wake clusters in the same manner described in Section 4.3 for CSPR departures. Again, as before, which of these capabilities would be implemented in the mature WakeVAS system would be determined by a consideration of the benefits and development risks of the various concepts.

The departure wake separation reductions that result from this procedure may be to standard radar separation or to intermediate values. When controllers time the release of aircraft for departure, the controllers anticipate separation when launching departures based on their experience with flight crew reaction times and relative aircraft performance. The mature WakeVAS system will consider these practices in designing the required operational concept and the interface of the required controller decision aid. For the safety of each departure, wakes (decay and/or transport) will be predicted very reliably during the period each departure is in the immediate path of its predecessor. To ensure safety, a real-time wake detection system will monitor the predictions of wake transport and decay. If the predictions are declared incorrect, they will be so declared before the succeeding aircraft is launched. In order to give the ground controller useful information to plan the departure sequence for each departure runway (i.e., staging) to optimize the available departure capacity, the wake prediction will be reliable out to 15 to 20 minutes in the future.

Another option that could be incorporated in the mature single runway departure concept is the application of VNAV and LNAV. In this option, a set of Area Navigation with VNAV departure paths would be set up for aircraft. The three dimensional paths for Large aircraft would be different than those for Heavies and B757s. Heavies typically take more runway to lift off. The VNAV paths for Large aircraft that are VNAV-capable would be set up to assure vertical separation from the leading Heavy or B757 aircraft on lift off. Additional safety may be built in through LNAV paths after lift off where possible. The challenges here would be the determination of standards to which aircraft VNAV conformance can be assured, and design of paths to provide adequate wake separation, given these tolerances. It would be expected that only certain Large aircraft would be capable of reliably achieving a path with a takeoff point substantially before the leading Heavy or B757, and an angle of ascent that exceeded the angle of ascent of the Heavy, so that the two paths maintain the required vertical separation. The VNAV procedures could include a bound on the furthest possible liftoff point on the departure runway for a specific trailing aircraft type and loading profile, as well as a minimum ascent angle. A corresponding VNAV procedure for the leading aircraft would also have a bound on the earliest possible liftoff point for the leading aircraft type and loading profile, as well as a maximum ascent angle. The ascent angle for the leader must be less than the ascent angle for the trailing aircraft. Reliable weights and any other condition affecting an aircraft's ability to take-off by a specified point on the runway such as surface winds must be reliably known to the decision tool being used by the controller to control aircraft departure clearance times. An indication of which aircraft could execute the required VNAV procedure would have to be provided to the tower controller prior to establishing the line-up sequence for that runway. Currently there is no room for additional type designators in the ARTS systems. However, other means might be devised or could be defined in STARS.

As in Section 4.3, LNAV and VNAV capabilities could also be used in refining definitions of departure corridors.

A decision support system would be needed to enable the controller to take the maximum benefit out of the mature WakeVAS departure system.

Since vertical separation must be maintained from the wake a leading Heavy or B757 aircraft, the maximum wake rise on the leading aircraft's departure path must be bounded based on an analysis of an extensive data collection of observed wakes in a variety of operational conditions. The dependence of the maximum wake rise on environment conditions (i.e., wind speed, angle, shear and temperature profile) will require that an active wind prediction and measurement system be incorporated.

Section 5

Methodology for Detailed Capacity and Benefit Analysis for Selected Procedures at Selected Airports

Since each airport has a unique geometry and traffic demand, they each have a different potential for using the wake vortex procedures described in the previous two sections. Therefore, to determine the benefits for such procedures, the most appropriate procedures must be paired with the airports most likely to use these procedures. This is depicted in Figure 5-1 as the first steps in determining the benefits of the wake vortex procedures.

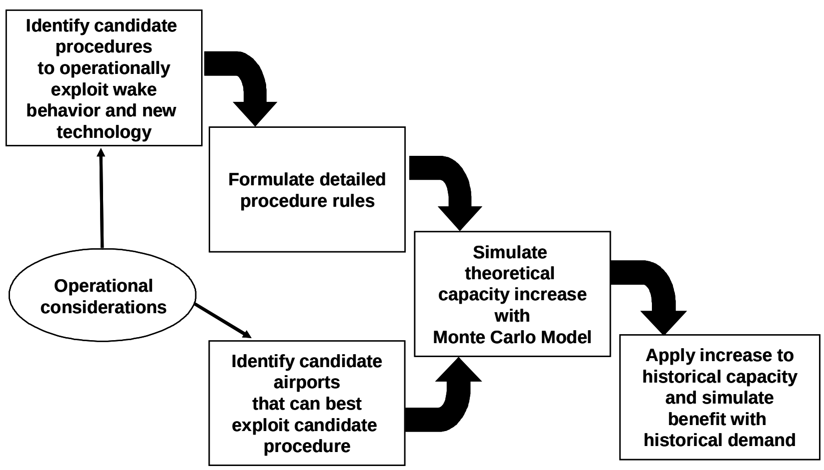


Figure 5-1. Overall Capacity and Benefit Methodology

After the pairing of airports and procedures, the arrival or departure capacity increases due to the new wake vortex procedures are simulated. These increases in arrival or departure capacity are then used to estimate the benefits derived from using the improved wake vortex procedures. The benefits are characterized by the portion of extra hourly arrival or departure capacity expected to be used at the airport, the decrease in the arrival or departure queue size, and the average minutes of arrival or departure delay reduction per aircraft.

5.1 Identification of Candidate Airports and Procedures

The procedures that have been selected for this study are the CSPR arrivals and departures and the single runway arrivals and departures. From past work, the improved wake CSPR procedures have proved to be beneficial. The single runway procedures can be used at any airport.

The airports at which these procedures are analyzed have to make operational sense. For instance, even though ORD has many Heavy and B757 aircraft in its traffic mix, it does not have closely spaced parallel runways. So the CSPR procedures are not analyzed at ORD. The airport/procedure combinations shown in Table 5-1 were chosen based upon discussion with the FAA/NASA Wake Vortex Stakeholders meetings in January and March 2002, and upon previous analysis by CAASD [25]. This analysis identified airports having significant excess arrival or departure demand and runway configurations amenable to using these procedures.

These airports have the runway geometries to support the procedures identified in the above table. However, some of the airports do not currently operate in this manner. The approach has been taken to analyze benefits for candidate CSPR procedures at an airport for arrivals or departures if one of the following conditions is true:

1. A CSPR pair is currently being used for the operation (i.e., for arrivals or departures), at least in visual conditions
2. A CSPR pair is intended to be used in the future at that airport (i.e., CLE)
3. A CSPR currently exists or in scheduled to be commissioned at the airport, and at most two runways will exist for simultaneous parallel jet operations, so there is a reasonable likelihood that the addition of a second or third dependent runway would provide incremental benefit during peak periods (i.e., EWR, LAX, PHL)

For instance, EWR has closely spaced parallel runways and it currently does not arrive or depart aircraft on both runways simultaneously because of airspace and environmental concerns. So any achievement of potential capacity benefits at EWR using the CSPR would be subject to the solution of these airspace and environmental concerns. All airports with CSPR not satisfying one of the above conditions for arrivals or departures will not have arrival CSPR or departure CSPR procedures modeled in this analysis, respectively, as there is no reasonable expectation that the CSPR would ever be used in practice.

Table 5-1. Airports Chosen for Specific Procedures

	Track C4 Steps 1-4	Track D1 Step 4	Track A3 Step 4	Track D2 Step 4		
Airport	CSPR Arrival Procedures	CSPR Departure Procedures	Single Runway Arrival Procedures	Single Runway Departure Procedures	Arrivals Simultaneous CSPR Use	Departures Simultaneous CSPR Use
ATL	▪	▪	✓	✓	None	None
BOS	✓	✓	✓	✓	4L/R	4L/R, 22L/R
CLE	✓	✓	✓	✓	Intend Use[9]	Intend Use
CLT			✓	✓	No CSPR	No CSPR
DFW		✓	✓	✓	None	17C/R, 18L/R, 35C/L
DTW		✓	✓	✓	None	3C/R, 21C/L
EWR	✓	✓	✓	✓	No Current Use[10]	No Current Use
JFK			✓	✓	No CSPR	No CSPR
LAX	✓	✓	✓	✓	24L/R, 25L/R	NoCurrent[11] Use
LGA			✓	✓	No CSPR	No CSPR
MEM	✓	✓	✓	✓	18C/L, 36C/R	18C/L, 36C/R
MIA			✓	✓	Future CSPR[12]	Future CSPR
ORD			✓	✓	No CSPR	No CSPR
PHL	✓	✓	✓	✓	No Current Use[13]	No Current Use
SDF			✓	✓	No CSPR	No CSPR
SEA	✓	✓	✓	✓	16L/R, 34L/R	16L/R, 34L/R
SFO	✓	✓	✓	✓	19L/R, 28L/R	1L/R
STL	✓	✓	✓	✓	12L/R, 30L/R	12L/R, 30L/R
Totals	9	11	18	18		

9 CLE adding CSPR in 2003, and intend to use these runways in visual conditions.

10 EWR only has single pair of CSPR as runways for unrestricted jet operations. These runways are not currently used for simultaneous parallel operations in visual conditions.

11 LAX only has two independent parallel runways for departures, so some incremental benefit may exist by the use of a third dependent runway, even though current operations do not use CSPR for departures

12 MIA adding CSPR in 2003, but has other independent runways for arrival and departure operation.

13 PHL only has single pair of CSPR as runways for unrestricted jet operations. These runways are not currently used for simultaneous parallel operations in visual conditions.

5.2 Capacity Estimation

The first step in estimating the benefits of a particular wake vortex procedure is to estimate the capacity increase that would be expected from the use of that procedure. The analysis reported in this paper is focused on the four procedures discussed above. Two of the procedures involve CSPR and the other two involve single runways.

For the CSPR, the basic feature of the wake vortex procedure is whether the conditions are conducive to transport the wake through the path of the aircraft approaching or departing the other runway. The conditions for this happening depend on the wind and the atmospheric turbulence. The wind primarily influences the transport of the wake and the turbulence influences the decay of the wake.

If the conditions indicate that the wake will not reach the other runway, then the separation between the aircraft on the two runways would be governed by the non-wake vortex spacing rules. Otherwise the current wake vortex rules would apply. For instance, if wake vortex is not a factor, aircraft on CSPR can be diagonally spaced by 1.5 nmi.[14] If wake vortex is a factor, then the wake vortex separation (e.g., 4, 5, or 6 nmi) has to be applied. The wake vortex dependence would not be needed in spacing the trailing aircraft on the upwind runway if the wake of a Heavy aircraft on the downwind runway cannot be transported to the upwind runway because of the magnitude of the wind. This would then increase the capacity of that runway pair under those conditions.

In the single runway case the current rules assume that the wake behind certain aircraft will persist for no longer than two minutes or a given distance, depending on the trailing aircraft. Again, if the conditions are right, the wake might exist in the corridor to be occupied by the trailing aircraft for a shorter period of time or for a shorter distance. The wake would either be transported laterally out of the corridor by a crosswind, would drop out of the corridor due to the inherent dynamics of the wake, or decay due to turbulence in the atmosphere. Thus, whereas a 4, 5, or 6 nmi spacing might be needed behind a Heavy or B757 aircraft, under certain conditions a 3 nmi radar separation would be sufficient.

The following section will discuss the use of NASA's AVOSS model of wake dynamics to determine when the wake will not be a factor for determining the interaircraft separations in the CSPR and single runway procedures. This will be followed by a discussion of the Monte Carlo techniques that were used to estimate the capacity increases that can be expected with the proposed wake vortex procedures.

[14] This is an operating assumption for this analysis. It must be confirmed by an appropriate safety analysis.

5.2.1 Use of AVOSS Data

The dynamics of the wake vortex is dependent on the aircraft that created it and the atmospheric conditions in which it exists. To account for the aircraft type dependence, all of the aircraft types comprising more than one percent of the scheduled traffic at the 18 airports of interest were listed. There were 85 types. The AVOSS model was run by NASA Langley staff on these 85 types of aircraft for five crosswind conditions (0, 5, 10, 15, 20 kts) and three turbulence levels (low – 1.0x10-7 m2/s3, mid – 1.4x10-3 m2/s3, and high – 3.0x10-3 m2/s3). For each run, the output of the AVOSS model gives the lateral position, height and circulation each second for both the upwind and downwind vortices. This process is depicted in Figure 5-2.

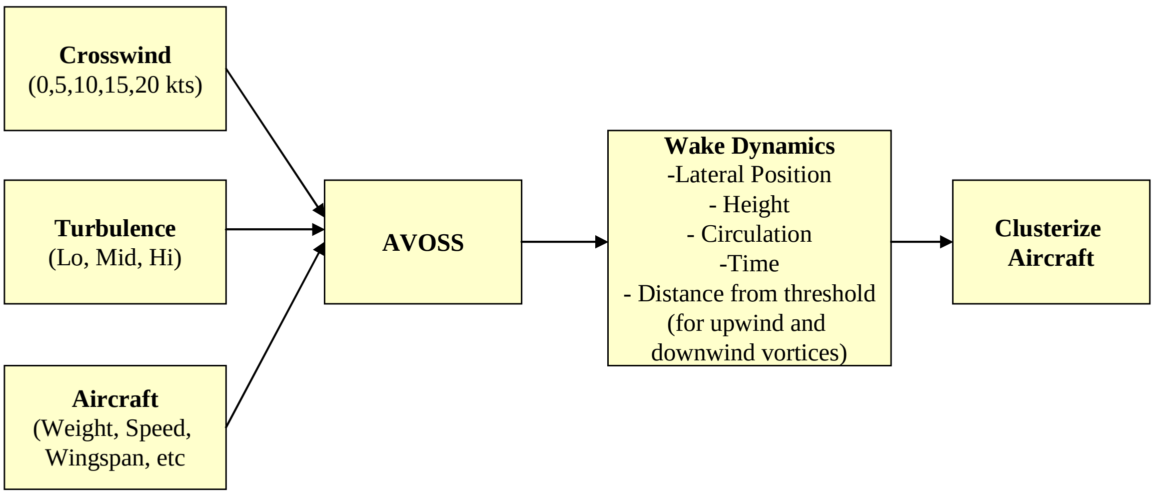


Figure 5-2. Initial AVOSS Processing

In order to take advantage of the differences in wake strengths among different groups of aircraft, the four categories (i.e., Small, Large, B757, and Heavy) were enlarged to eight clusters (see Table 5-2). These clusters will be used to define the wake characteristics of the leading aircraft. The trailing aircraft will still be characterized as Small, Large, and Heavy. (a B757 is considered to be a Large trailing aircraft). Except for a couple of exceptions, the clusters were defined based on the initial wake strength (circulation).

Table 5-2. Aircraft Cluster Definitions

Initial Wake Strength (m^2/sec)	Cluster	Current Category
0 to 69.99	8	Small
70 to 89.99	7	Large
90 to 129.99	6	Large
130 to 149.99	5	Large
150 to 205.99	4*	Large
B757	3**	B757
206 to 249.99	2	Heavy
250 and above	1	Heavy

* B727-200 moved to cluster 4 due to wake decay characteristics

** Separate cluster for B757s, put in order to be able to match the clusters to the definitions in the Controllers' Handbook (7110.65)

5.2.1.1 CSPR Procedures

The AVOSS model used for inputs this study was the version used to model the wake dynamics of arriving aircraft. For lack of another model for the lateral transport of wakes from departing aircraft, we assumed the logic described below would be used for both arrivals and departures. The result of the logic will be an indication of under what conditions a runway is "wake independent" of another CSPR. The logic is depicted in Figure 5-3.

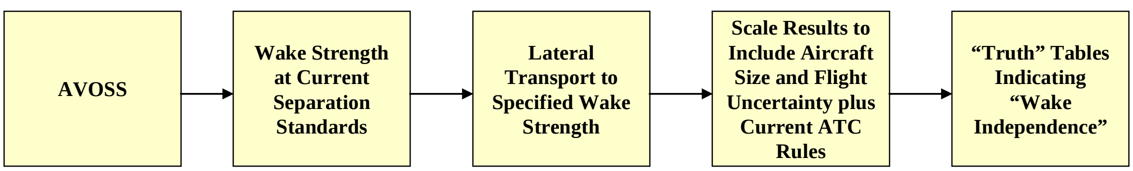


Figure 5-3. Lateral Transport Logic

As part of the wake vortex procedures, additional technologies will be added to the system to yield benefits of increased capacity and reduced delays. The initial technologies would be wind-based and the more advanced technologies would measure turbulence and would detect and predict the path of the wakes.

The lateral transport of the wake was determined for decay of wakes to the background level (70 m^2/s). The wind advects the wake and the turbulence is a major factor in the decay of the wake. It was found, however, that the low turbulence value was extremely low, causing the wake to persist for a very long time. Therefore, we made a simplifying assumption that the low turbulences correspond to the low winds and the high turbulence value corresponds to the high winds. Specifically, we assigned low turbulence to the 0 kt wind case, mid level turbulence to winds of 5 through 10 kts and high turbulence to the 15 kt through 20 kt wind.

To determine the runway spacing that would support this situation, one has to add half the wing span of the leading aircraft and the trailing aircraft as well as the uncertainty of the aircraft about the extended runway centerlines. In all of these computations, the in ground effect (IGE) wake dynamics were used.

Based on the results of this process, several of the runway spacings, particularly behind Heavies and B757s, were greater than the 2500 feet that is the standard in today's system. Furthermore, under certain conditions, the wake of Large aircraft are transported more than 1000 feet. The current FAA wake program is collecting wake data in the field to show that the wake behind a Large does not travel more than 1000 feet. We have assumed here that the FAA successfully proves that hypothesis. Therefore, we scaled the resulting required runway spacings to conform to the current operational standard *and* to the hypothesis that wakes behind Large aircraft will not be transported more than 1000 feet under conditions that are usually prevailing at an arrival runway.

Once the required runway spacings are determined, then a set of "truth" tables can be constructed that indicate whether there is "wake independence" of an aircraft category (i.e., Small, Large, Heavy) behind another aircraft category or cluster for a given crosswind and runway spacing. This "truth" table is used to model the arrival and departure capacities.

An option was also generated to represent the ability to determine varying levels of circulation that an aircraft may safely be certified to encounter, based on its weight category. This was based on considering an adjustment in the hazard level to accommodate the roll authority of the aircraft.

5.2.1.2 Single Runway Procedures

Modeling of single runway arrival and departure procedures would be based on decay, sink and lateral transport of wakes. Specific single runway modeling was not accomplished in this task in this fiscal year.

5.2.2 Procedure Evolution to Be Analyzed

As described in Section 3, each type of procedure (e.g., CSPR, single runway) can have evolutionary steps depending on the amount of technology that is introduced into the system. Several potential evolutionary steps can be defined for each type of procedure with some steps having substeps. For CSPR, the steps shown in Table 5-3 will be analyzed. By agreement with NASA, only the CSPR Arrival procedure will be analyzed based on evolutionary steps. The other procedures will consider only the mature step.

Table 5-3. Evolutionary Procedure Steps

Step	Relation to AVOSS Output
1	Use crosswind to allow wake independence of upwind runway, adding a safety buffer to minimum crosswind required
2	Use crosswind to allow wake independence for both runways if the wind is low enough, judging the wake transport of leading wake **category** aircraft to the 70 m^2/s level, adding a safety buffer to minimum crosswind required
3	Use crosswind to allow wake independence for both runways if the crosswind is low enough, judging wake transport of leading **cluster** aircraft to the 70 m^2/s level, adding a safety buffer to minimum crosswind required
4	Use crosswind to allow wake independence for both runways if the crosswind is low enough, judging wake transport of leading **cluster** aircraft at a level dependent on the weight class of the trailing aircraft, adding a safety buffer to minimum crosswind required
5	Use crosswind to allow wake independence for both runways if the crosswind is low enough, judging wake transport of leading **cluster** aircraft at a level dependent on the weight class of the trailing aircraft, without adding a safety buffer

5.2.3 Monte Carlo Techniques

The most straightforward method of estimating the arrival or departure rates taking into account the features of the potential wake vortex procedures is to simulate the stream of aircraft arriving or departing the runways. The actual mechanism used to control the simulation was an add-in to Microsoft® Excel called @Risk by Palisade. The remainder of this section will give a high level description of the simulation models that were used to estimate the arrival and departure rates.

5.2.3.1 Arrival CSPR Modeling

Consider the stream of aircraft approaching a pair of closely spaced parallel runways as shown in Figure 5-4. The crosswind is from the left as the aircraft approach the runways. The first aircraft lands on the upwind runway at time T_0. The aircraft happens to be a Heavy. The next aircraft on the other runway is randomly chosen by the simulation to be a Heavy also. However, when the simulation goes into the “truth” table (described above) for this wind and runway spacing it finds that the wake from the Heavy aircraft on the upwind runway can indeed be transported to the downwind runway. Therefore wake vortex separation is needed behind the leading Heavy aircraft. This is the minimum separation behind the aircraft landing at T_0. The simulation also adds a randomly chosen additional distance to represent any buffers that the controllers add to compensate for uncertainties in the system. The resulting landing time for the second aircraft is computed to be T_1.

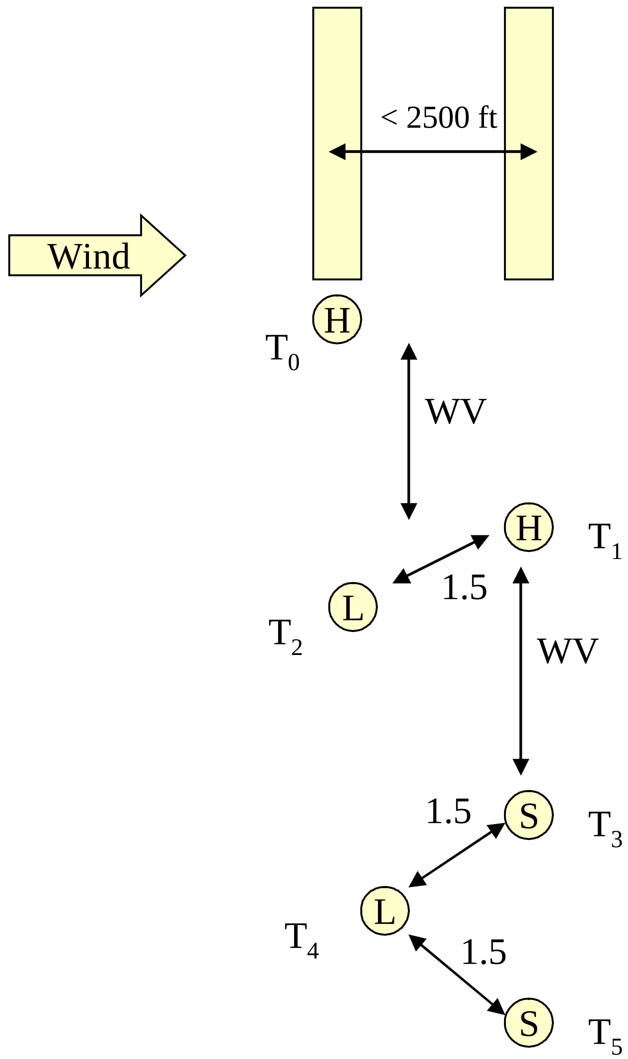


Figure 5-4. Arrival CSPR Modeling

Now consider the third aircraft. The wind is of a magnitude that the "truth" table tells the simulation that the wake of the Heavy will not be transported as far as the upwind runway. Therefore, the minimum diagonal spacing can be 1.5 nmi.[15] After the buffer is added, the aircraft lands at T_2.

15 As noted previously, this is an operating assumption for this analysis. It must be confirmed by an appropriate safety analysis.

The fourth randomly chosen aircraft is in the Small category. From the "truth" table it could be spaced 1.5 nmi diagonally behind the Large aircraft on the upwind runway. However, the aircraft immediately ahead of it on the same approach is a Heavy. The wake vortex separation behind this aircraft would be the constraining separation. After adding the buffer the fourth aircraft lands at T_3.

The fifth and sixth aircraft can take advantage of the 1.5 nmi diagonal rule and land at time T_4 and T_5, respectively.

This process is repeated for 50 aircraft on each runway. The simulation then takes the landing time of the first aircraft and subtracts it from the landing time of the last aircraft and divides the result by one less than the total number of aircraft to determine the arrival rate. This process is repeated 500 times and the average arrival rate is computed.

Notice that in the example in Figure 5-4, out of five aircraft pairs, one pair was able to take advantage of the new wake vortex procedure. This results in an increased arrival rate for this procedure. A single runway arrival rate was also estimated as a baseline using the current spacing rules.

For the CSPR arrival procedure, all four steps and their substeps were modeled to estimate the arrival rate improvements over the evolution of the procedure with the introduction of additional technology at each step.

5.2.3.2 Departure CSPR Modeling

In the arrival modeling, by the time the aircraft are at their minimum separation they are flying at nearly their final approach speed. Thus, to estimate the landing time it is sufficient to calculate the time it takes them to travel the separation distance at the final approach speed.

Some of the departure rules involve a direct application of time (e.g., cleared to roll two minutes after the previous aircraft started to roll). However, some of the departure rules take the form of "maintain x nmi separation when both aircraft are airborne" or "insure that the leading aircraft is at least 6000 feet (down the runway) and airborne." To bring all of these rules to a common reference point we can compute the difference in the time to start rolling as the analog to the arrivals passing over the runway threshold. To make this computation we need a model of the departure process. The basic features of this model are shown in Figure 5-5.

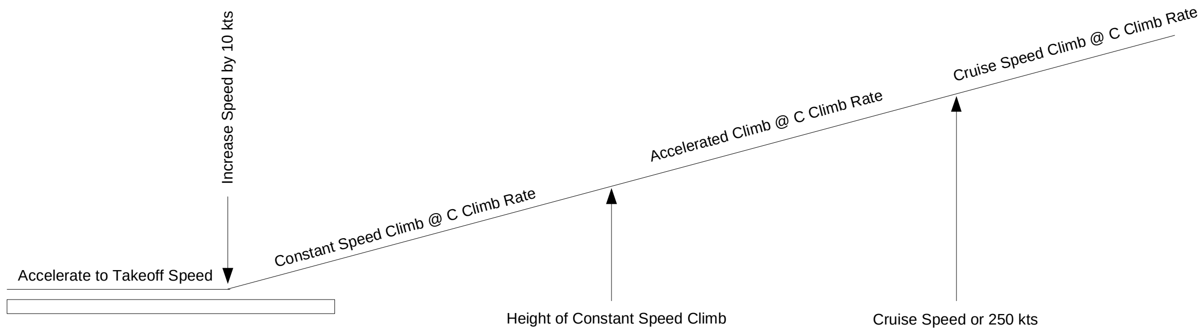


Figure 5-5. Departure Model

When the simulation randomly selects an aircraft category (Small, Large, B757, Heavy) or a cluster (cluster 1 through 8) it also randomly selects from within that category or cluster a specific aircraft type (e.g., B727-200). Each aircraft type has a set of parameters implied by the model depicted in Figure 5-5. Thus, the simulation can estimate the position, speed and altitude of an aircraft at any time after its start of roll time.

The departure rules have more variations than the arrival rules. Departures can be on single, CSPR, independent runways or intersecting runways. They can be conducted under visual or non-visual rules, depending upon whether or not the ATCT can apply visual separation of a departure from the preceding one or not. If the departures are on parallel runways, the runway thresholds can be displaced or not. After the departure leaves the ground it either goes straight out or it can be turned away from the centerline of the runway. Each combination of these conditions involves a different set of rules. The rules that were used in this analysis pertain to CSPR operating under visual conditions and the aircraft are fanned (i.e., turned away from their respective centerlines) after departure. Whether the runway thresholds are displaced or not depends on the specific airport. A discussion of the departure rules from FAA Order 7110.65 is presented in Appendix B.

An example of the modeling of CSPR departures is shown in Figure 5-6.

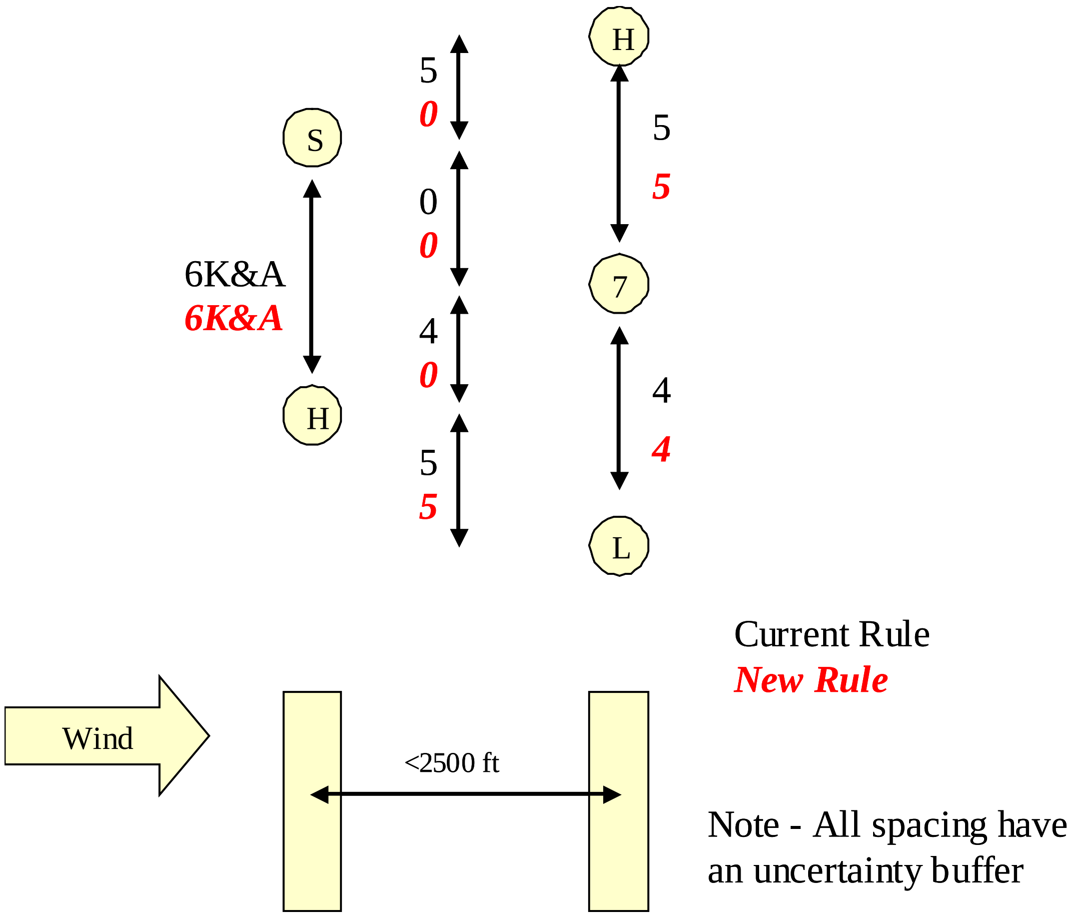


Figure 5-6. Departure CSPR Modeling

Assume that the first aircraft departs in visual conditions on the downwind runway and is a Heavy. If a Small aircraft departures on the adjacent closely spaced parallel runway the current rule says that it needs to be 5 nmi behind the Heavy when it becomes airborne. If, however, the new rules were in effect, the "truth" table (the same one that was used for the arrival case) might tell us that for this runway spacing and wind the Heavy would not be a wake factor on the adjacent runway. Therefore we could release the Small simultaneously with the Heavy. Under both the current and new rules there would also be a randomly chosen uncertainty buffer representing the delay in time for the second aircraft to start its roll. This could be due to pilot-controller communications, last minute cockpit coordination, pilot discretion, or whatever. The magnitude of this buffer is chosen to give departure rate results that are consistent with actual departure rates.

The third aircraft is a B757. Under both the current and new rules it could be released simultaneously with the second aircraft on the other runway. However, it is required to be 5 nmi behind the Heavy aircraft in any case so that determines its easiest roll time.

The fourth aircraft is a Heavy on the upwind runway. Under the current rules it has to be 4 nmi behind the B757 on the downwind runway when it becomes airborne. This is the constraining condition because the Small aircraft in front of it has to be only 6000 feet and airborne. Because the B757 is on the downwind runway, the “truth” table will tell us that wake separation is not an issue under the new rules. Therefore, the 6000 feet and airborne rule becomes the constraint.

The fifth aircraft departs on the downwind runway. In has to be five nmi behind the Heavy aircraft on the upwind runway under both the current and new rules because the “truth” table tells us that for this runway spacing and wind the wake can be transported over to the downwind runway.

For the four pairs of aircraft departing the alternating runways in the example in Figure 5-6, two of the pairs can take advantage of the new rules by decreasing the spacing between departures. This will, in turn, lead to a greater departure rate.

The departure simulation runs 25 aircraft off of each runway and repeats this experiment 250 times to estimate an average departure rate. Less aircraft and less runs in this case versus the arrival CSPR simulation were predicated on the length of time it takes to model each aircraft departure. Each departure has to be modeled in conjunction with the aircraft ahead on the same runway as well as the aircraft ahead on the other runway.

For CSPR departures, only the “truth” tables corresponding to step four of the procedure evolution were used. This would represent the upper bound of the departure rate improvements with the technologies under consideration.

5.2.3.3 Arrival Single Runway Modeling

The detailed modeling of single runway arrivals would be based on the decay, sink, and lateral transport of wakes at the runway threshold and at several other points extending out to a distance that includes the outer marker for an ILS approach. This type of modeling was done for the AVOSS experiments in 2000 at DFW. What was not done at that time was to assess the effects of using an evolution of technologies. Additional runs of the AVOSS model will be needed to make this assessment.

5.2.3.4 Departure Single Runway Modeling

The detailed modeling of single runway departures would be based on the predicted decay or lateral transport of wakes starting at the point of aircraft rotation and continuing out to a distance at which the departure paths diverge. Additional runs of the AVOSS model will be needed to reflect the parameters of a departing aircraft needed to judge the decay characteristics of the wake.

5.2.4 Comments on the Use of the Capacity Estimates

The arrival and departure rate estimates that have been described above assume that the runways are dedicated to either arrivals or departures, not both arrivals and departures on the same runway. This is not the case at many of the airports that are being studied. Each airport operates their runways in a manner that provides them an “operational advantage.” If the airport serves heavily loaded Heavy aircraft, for instance, those aircraft will depart on the airport’s longest runway regardless of any other strategy for operating the airport. This effect has not been modeled in this investigation. We do not know the nuances of the operations at all of the airports.

However, there are some ways to model the operations to reflect some of these features. For instance, a dedicated departure runway may achieve a rate of 55 departures per hour. However, with arrivals using that same runway the departure rate might be nearer to 45 departures per hour. Thus it is prudent to calibrate the model to the lower departure rate as a more realistic value in the majority of the cases. The same can be said of modeling the arrival rate when departures share the runway.

Another assumption of the models to estimate the arrival and departure rates is that the mix of aircraft is representative of the time period being modeled. The mix that we usually use is that which the airport experiences over a long period of time. This, in fact, may be representative for shorter periods of time at some airports. However, at some of the international airports there are periods of time when the Heavy aircraft population increases as overseas flights arrive and depart. Since wake vortex procedures are sensitive to the number of Heavy aircraft in the mix, this is potentially an important aspect of using these arrival and departure rate estimates.

5.3 Benefit Estimation

Approach and departure procedures typically have a varying effect on airport capacity, depending on the traffic mix using the procedure at an airport (e.g., how many Heavy aircraft), the performance of the controllers and flight crews in attaining separations close to the stated minimums, wind conditions affecting compression on final, etc. Procedures that affect airport capacity can have a very large impact on throughput and delays, but the impact is very sensitive to the pattern of demand and weather on a particular day.

This benefit modeling approach is a fast-time model that simulates the effect of increased capacity on throughput and delay over an entire operational year, in the time periods where the procedure would be used. This simulation uses FAA-recorded weather, demand, operations counts and tower specified arrival and departure rates as baseline inputs, instead of the approach of using a characteristic "typical" or "worst case" day.

For the procedural analysis described in this paper, a large number of scenarios need to be considered quickly, so that parameters can be modified to see the effect on benefits of changing particular assumptions. The benefit estimation model described here, developed by CAASD, is intended for screening a large number of procedural concepts at various airports, not for modeling a procedure at a specific airport in great detail. For highly detailed modeling of a specific procedure at a specific airport a higher fidelity model would be appropriate.

The primary goal of this benefit estimation model is to simulate the effect of an anticipated capacity increase under very specific conditions using actual historical demand and weather conditions over a long period of time, then estimating of the amount of additional utilized capacity, and the resulting reduction in delays. A typical PC computes the results in 1-2 minutes for a single airport and procedure model, for an entire year. The benefit estimation model can also factor in future capacity changes (e.g., new runway construction) and increases in demand, such as that forecast by the FAA in the Terminal Area Forecast (TAF). The TAF contains the FAA's forecasts for 474 airports receiving FAA and contract tower services, covering fiscal years 2002-2020 projected operations.[16]

This model has several limitations. These limitations do not affect its ability to provide a basic ranking of potential delay benefits of future procedures and airports in an initial screening analysis, which is its intended use here. The limitations are as follows:

- Network effects of delay reductions throughout the NAS, also referred to as "delay propagation," are not modeled. These effects depend on the capacity constraints elsewhere in the system (e.g., other airport capacities and en route constraints) for a particular time period. The additional effort to adequately model the network effects for specific historical time periods in this simulation, and the great increase in computational complexity, are not warranted for this level of analysis, where basic changes in procedural assumptions will have a much greater effect on benefits than the likely network effects.

- Constraints on traffic flow other than the subject airport's runway capacity are not modeled. For example, airport surface taxiway limitations and arrival fix throughput constraints are not modeled. These constraints would be a key issue in the use of a

[16] From introduction to FAA TAF at http://www.apo.data.faa.gov/tafintro.htm

new procedure concept that used runways in a different configuration than is done currently. Situations where current operations do not use a particular runway configuration modeled for a new procedure will be identified in the analysis. An example would be simultaneous use of EWR 4L/4R for arrivals in IMC conditions using a new procedural concept for CSPR arrivals. These runways are not currently used in visual conditions for simultaneous arrivals, so modeling benefits for this operation in IMC would require that the surface taxi pattern and arrival fix capacity existed to utilize this new procedure. Inclusion of these added details would require a more in-depth analysis.

- Arrival and departure capacity are not explicitly traded off in the model when runways are being used for both operations simultaneously, and when enough of arrival and departure demand exists to make such a trade-off necessary. The model uses the Airport Acceptance Rate (AAR) and Airport Departure Rate (ADR) called by the ATCT for that time period, so it does implicitly include the effect of arrival versus departure capacity tradeoff made by the tower in setting their rates for Traffic Flow Management, but it does not model the impact, if any, of increasing the operational capacity (e.g., arrivals) affected by the proposed procedure on the operational capacity of the other operation (e.g., departures). Such arrival-departure capacity elasticity can be modeled, but requires that other detailed considerations, such as surface taxi patterns, be considered, for an accurate result.
- Individual aircraft are not modeled. The model is an aggregate model, modeling traffic demand and operations counts (i.e., landings and take-offs) in discrete 15 minute periods. However, the capacity increases used as input are simulated in the separate Monte Carlo Capacity Simulation for the weather conditions, and runway configuration being used for the proposed new procedure concept in each time period, and the average traffic mix used over the entire day.

The following sections will describe the benefit estimation model used, including the inputs, key model logic and outputs.

5.3.1 Model Inputs

The benefit estimation model takes the previously simulated capacity benefit for a specific airport and procedural concept and applies the effect of that capacity increase on throughput and delays over a substantial period of historical time, typically one year. For that time period, the ASPM database is used to provide the necessary baseline parameters needed to model the potential airport benefit.

5.3.1.1 Airport Data Input

The baseline airport information, containing the airport operational data to which the new procedures are applied, is provided by the ASPM database. This data base is a FAA-APO information system that merges the following data sources:

- ETMS, which provides expected time of runway departure and expected time of runway arrival for each flight in system with filed IFR flight plan
- Airline Service Quality Performance (ASQP), which provides airline data on Out (i.e., push-back from gate), Off (i.e., runway take-off), On (i.e., runway landing) and In (i.e., gate arrival) times, as well as the scheduled time of gate departure and gate arrival, for flights of air carriers reporting this data. Carriers having more than one percent of the total domestic scheduled passenger revenues (currently ten) are required to submit their performance data to the DOT for inclusion in the ASQP database. This data is typically provided 6 weeks after the end of each reporting month
- Out, Off, On, In (OOOI): an alternative source of out, off, on and in times for flights in addition to those reported in ASQP, for 10 domestic airlines reporting at 80 domestic airports
- ATCT provide the hourly
  - AAR and ADR, which are the expected landing rate and take-off rate per hour called by the tower for traffic flow management purposes. ASPM distributes this capacity uniformly to the four periods in each hour
  - Update of runways being used for arrivals and for departures
- Airport surface weather data: wind speed, wind direction, ceiling, visibility and ambient temperature, recorded hourly with occasional intra-hour updates

This information provides a complete picture of arrival and departure demand, actual throughput, capacity, runway configurations and weather conditions for each 15 minute period during a 24 hour day. Data is available for selected airports starting in January 2000.

ASPM provides an expected unimpeded landing time or take-off time, which is used in our benefit analysis as the time at which a flight is added to the arrival or departure demand queued to use the airport runways. The expected unimpeded landing time is the estimate of when a flight would land based on the actual take-off time plus the estimated transit time from take-off to landing, not including ground delays encountered before the actual take-off time or any estimate of delays encountered en route.[17] For flights that are included in a

[17] The actual take-off time is determined using a ASQP or OOOI Off time or ETMS departure message time. The added transit time is determined by the filed Estimated Time Enroute (ETE).

Ground Delay Program (GDP) for the arrival airport, the original filed departure time from ETMS is used instead of the actual takeoff time, as the original filed departure time reflects the user's desired takeoff time, and the GDP is put into affect to reflect reduced capacity at the arrival airport, which is a primary factor in determining arrival delays. The expected unimpeded landing time is thus a measure of the user's desired landing time at time of departure, prior to the inclusion of system constraints, and is used as the basis from which arrival delays are calculated in this model.

In a similar fashion, the expected unimpeded take-off time for a flight is calculated as the ASQP or OOOI Out time plus an estimate of the unimpeded taxi-out time for that airport and carrier, which is made in ASPM, or alternatively is based on the originally filed takeoff time from ETMS. This expected unimpeded take-off time thus reflects the user's desired takeoff time at the time of push-back, and is used as the basis from which departure delays are calculated.

Note that both of these expected unimpeded times are not equivalent to an air carrier's scheduled gate departure or gate arrival times, which are the times given to the flight's passengers. These scheduled times are not relevant for unscheduled carriers and general aviation flights. The use of scheduled gate out and in times also requires the modeling of taxi-out and taxi-in delays, which are not included in this analysis.

5.3.1.2 User/Procedural Specific Inputs

The following section describes in detail the inputs to the model that refer strictly to a candidate procedure (or procedures) being analyzed. The user builds a set of input parameters for the modeling of either an approach or departure procedure. In addition, the following control parameters are provided to the model for each airport and procedure combination:

- Upper and lower bounds for ceiling, measured in feet, and visibility, measured in statute miles, for which the candidate procedure is being applied.
  - For candidate arrival procedures considered in this document, set the lower bound to Category I minima and the upper bound to visual approach minima. This is because the candidate arrival procedures would only be applied where visual approach conditions do not apply.
  - For candidate departure procedures considered in this document, set the lower bound to the tower visual departure separation minima, and the upper bound above the maximum recorded values (e.g., 99,999 feet and 999 miles). Different baseline departure separation rules exist for conditions where the tower visual departure separation minima do not apply. The corresponding capacity benefits for the candidate procedures in these non-visual conditions are typically much lower than for the visual case.

- The maximum crosswind limit for operational use of a runway, typically set to 30 knots.
- The maximum tailwind limit for operational use of a runway, typically set to 10 knots.
- Baseline Capacity Limit (BCL), the use of which is described in the next section.
- Multiple Baseline Runway Adjustment Factor (MBRAF), used to adjust the calculated capacity benefit where baseline capacity includes more than one runway. The use of this parameter is described in the next section.
- An ASPM runway flag to use actual runways reported in the database for the candidate procedure, or to use the runways with the best capacity for the actual wind conditions of the specific time period.
- For each airport, procedure, runway direction and crosswind level (if needed), provide the baseline capacity and candidate procedure capacity in operations per hour, as simulated by the Monte Carlo simulation. For candidate arrival procedures this refers to the arrival capacity, for candidate departure procedures this refers to the departure capacity.

Time periods are selected during the model set-up from the historical period contained In the data base. This temporal selection can be made by hour of day, day of week and/or specific date. For this analysis, the period of 6 AM to midnight local time is used for all days in the historical period, which is calendar year 2002.

5.3.2 Model Logic

The model logic iterates through each 15 minute time period in the time horizon being modeled, which is typically all of the periods from 6AM to midnight local time for all of the days in a year, or 26,280 time periods in a 365 day year. For illustration, an arrival procedure simulation is discussed in this section. Note that the process is essentially the same for departure procedure simulation.

The initialization steps for a specific procedure and airport are:

- Input baseline and new procedure capacities, in operations per hour, as simulated by the Monte Carlo capacity simulation process described earlier in this section.
- Read in all user input parameters.
- Initialize time period index to one.
- Initialize the baseline and new procedure queue lengths to zero. This model simulates two separate queues, which represent the baseline and new procedure cases, respectively. Updated in each time period, the queues contain the amount of arrival

demand available to use the airport's total arrival runway capacity at the beginning of each time period.

The main steps in the computation are:

1. Read the ASPM data for that time period, as described in the previous section. Add the arrival demand to the baseline and new procedure queue for the beginning of the period. Initialize the Capacity Expansion Factor (CEF) to 1.0 as a default value (i.e., default is no capacity expansion).
2. Determine if the required ASPM data fields have valid data for the model: arrival and departure throughputs, arrival and departure demand, AAR and ADR, airport visibility, wind speed, wind angle and visibility. If not, skip to Step 6 (i.e., use default CEF of 1.0).
3. Determine if the ceiling and visibility conditions required for the proposed new procedure exist. If ceiling is not available, check only visibility. Ceiling values are not reported for all time periods, but visibility is typically always listed. If this test is not passed, then skip to Step 6 (i.e., use default CEF of 1.0).
4. Based on the user input parameters, determine what different runway arrival combinations can be considered for use in the time period, or use the current runway configuration only. Check the cross winds and tailwinds on each runway configuration to determine if each candidate arrival runway configuration meets these requirements, and exclude those that do not from further consideration in the time period.
5. Calculate the CEF to be used for the procedure at that airport for each potential runway combination (RC) that could be used.

   (a) CEF(RC) = 1 + (MBRAF * ((NPC / BPC) -1)), where

      i. MBRAF = Multiple Baseline Runway Adjustment Factor, which is 1.0 for single runway baseline operation and one or two runway new procedure operation, < 1.0 otherwise

      ii. NPC = simulated Monte Carlo New Procedure Capacity in operations per hour

      iii. BPC = simulated Monte Carlo Baseline Procedure Capacity in operations per hour, $BPC < NPC$

      iv. Note that CEF(RC) is greater than or equal to 1.0

6. Calculate the capacity increase (CI) for the new procedure in this time period, for each specific RC which could be used for the procedure.

   (a) CI(RC) = max(min(ASPMC, BCL) * CEF(RC), ASPMC) - ASPMC, where

i. ASPMC = ASPM capacity limit, which is the AAR for arrivals[18]

ii. BCL = Baseline Capacity Limit, which is upper bound on the baseline procedure arrival capacity for that airport, input by the analyst

(b) The formula is based on the desire to limit the new procedure capacity to be greater than or equal to the current baseline capacity under all conditions, and to not exceed BCL * CEF, unless the current ASPM capacity exceeds BCL * CEF, in which case it is used instead. In cases where the baseline capacity is less than BCL, the capacity increase is scaled to the current baseline capacity. In cases where the baseline capacity is greater than the BCL, the capacity increase is limited so that the new procedure capacity is limited to BCL * CEF

7. Pick the runway combination to use for the procedure where CI(RC) is maximized.

8. Determine the amount of arrival demand satisfied by the baseline procedure capacity, ASPMC, and the new procedure capacity ASPMC + CI. Save the remaining demand in the two queues after applying the capacity for the next period. Assume all available capacity is used to satisfy arrival demand for both the baseline and new procedure case, so there is no “demand latency” due to en route delays or other constraints encountered between take-off and landing not included in this model. This assumption will provide simulated baseline behavior that is different than the actual baseline behavior, which does include this demand latency. However, to ensure that the same assumptions are used for both the baseline and new procedure delay calculation, the actual throughputs are not used for the baseline case.

9. Calculate the delay under the baseline and new procedure as the delay accruing to the demand remaining in the queue at the end of the time period.[19]

10. Calculate and write out the detailed simulation statistics output for the current period, and accumulate the statistics for the summary statistics reported at the end of the simulation horizon. Both the detailed simulation statistics and summary statistics are discussed in the next section.

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18 As an additional adjustment, the AAR is revised upward if the average of actual arrival counts for the current period, the previous period and the next period (i.e., 45 minute average) exceeds the AAR for the time period. The AAR is revised to match that 45 minute average. This adjusts for periods when actual airport throughput exceeds the stated capacity.

19 This description is an oversimplification of the actual model logic. Each 15-minute period is broken into three 5-minute periods, with a proportional distribution of capacity and a randomized uniform distribution of demand. This additional simulated detail allows a more accurate estimation of arrival delays.

11. If the current period is the last period to be modeled, end the simulation. Otherwise, increment the time period index to the next period to be simulated. If the next period is beginning the next operational day (i.e., there is a time gap between the current and next period), reinitialize the baseline and new procedure queues to zero initial length. The remaining demand at the end of an operational day is not carried over to the next day.

12. Go to back to Step 1.

Add the delays under the baseline and new procedure simulations for the entire time period and divide by the number of total arrivals to get the average arrival delay per flight and by the number of days in simulation to get average arrival delay per day (in minutes).

5.3.3 Model Outputs

Summary results for entire simulation time horizon are provided for the following data elements:

- Hours with necessary data. This includes all time periods where the necessary data fields have valid values, as discussed in a previous section.
- Hours meeting procedure conditions. This includes all periods with necessary data where the weather conditions required for the procedure are met.
- Hours meeting all conditions. This includes all periods meeting procedure conditions where arrival demand in excess of the AAR exists.
- Average baseline and new procedure capacity under required conditions. The average for the two capacities over periods where procedure conditions are met. Note that these average capacities may be different than the simulated capacities provided by the Monte Carlo simulation, as the Monte Carlo simulation estimates steady-state runway capacities under standardized conditions across all airports, while the baseline capacity in this model is based on the reported AAR. The new procedure capacity, likewise, is a function of the reported AAR.
- Total demand not satisfied in time period desired in baseline procedure case. This is the demand that has an estimated unimpeded arrival time in the current period that is carried over to the next time period, summed over all time periods. Demand is modeled as being satisfied first-come, first-served.
- Additional demand satisfied in time period desired in new procedure case. This is the portion of the demand not satisfied in the period of arrival to the queue in the baseline simulation that is satisfied in the new procedure simulation, summed over all time periods.
- Total extra capacity provided by new procedure over all time periods.

- Total extra capacity used by new procedure over all time periods. Baseline capacity is modeled as being used before the additional capacity is used.
- Total baseline and new procedure delay, which is the total time in queue for all arrivals for the baseline and new procedure cases.
- Total delay benefit = total baseline delay – total new procedure delay.
- Total number of arrivals over all periods.
- Average delay reduction from new procedure per aircraft = Total delay benefit / Total number of arrivals over all periods.
- Average delay reduction from new procedure per airport per day = Total delay benefit / Number of days in simulated horizon.

The model also provides the following output information for each 15 minute time period, in addition to the input data provided by ASPM:

- Flags indicating that the following conditions are met
  - Necessary data exists
  - Procedure conditions are met
  - All conditions are met
- Runway direction used for CSPR procedures, with cross-wind and head-wind levels
- The record key that is used to pick a specific set of simulated baseline and new procedure capacity numbers, based on airport code, procedure label, runway direction and cross-wind
- Calculated CEF, which is described in the previous section
- Demand entering queue, demand satisfied and remaining demand in queue, both for baseline and new procedure case
- Extra demand satisfied by new procedure

Section 6

Concept of Use for a CSPR Arrival Wake Procedure

This section presents a concept of use for a CSPR arrival procedure that takes advantage of the knowledge of winds and the initial intensity of wakes generated by different types of aircraft. This procedure corresponds to evolution step (d) described in Section 4.

An overview of this arrival procedure will be presented, along with system architecture requirements and an event sequence illustrating operational use. Issues from the perspective of controllers and flight crews will be discussed as well as the relationship of this concept to other government and industry concepts.

6.1 Description of Concept

Current arrival procedures require parallel runways spaced less than 2500 feet apart to be treated as a single runway unless pilots can provide visual separation during arrivals and take responsibility for wake avoidance. Many airports transition from the use of visual approaches to instrument approaches when the cloud ceiling drops below 3000 feet or so AGL. At airports with runways spaced less than 2500 feet apart, this results in reduced capacity due to the need to treat the parallel runway pair as a single runway. The 2500 foot rule applies equally to the following two pairs of arriving aircraft:

- a B747 arriving on one runway and a Cessna 172 arriving on the parallel
- a Cessna 172 arriving on one runway and another Cessna 172 arriving on the parallel

Wake observations and modeling efforts indicate that aircraft with different weights, speeds, and wingspans can generate very different wake intensities. One aspect of the candidate CSPR arrival procedure takes advantage of these differences in wake intensity by clustering aircraft of similar initial wake intensity together into eight wake clusters. Appendix C shows the wake cluster assignments used in developing this concept for aircraft types most common to busy airports. The maximum initial wake intensity generated by any aircraft in a cluster is assigned as the representative wake intensity for all aircraft in that cluster. So, if a B747 is approaching one runway (a Cluster 1 aircraft), a 2500 feet spacing would still be required for the parallel runway to not have to add wake vortex separation from the B747. But if a B737 is approaching the same runway, it is only a Cluster 4 aircraft and generates less than half the wake intensity of a B747. This could allow arrivals on the parallel runway to arrive without applying wake separation for runways spaced significantly less than 2500 feet.

A second aspect of the CSPR arrival procedure is that even though wakes tend to transport with the wind, the current 2500 feet rule applies equally for all wind conditions. Consider the case where a B747 is arriving on one runway and the wind is such that the wake will be transported away from the approach path to the parallel runway. In this case, aircraft could safely arrive on the parallel runway without applying wake separation from the B747. Given the wake characteristics of a B747, its wake can be expected to transport further against a crosswind than the wake of a B737. Thus, if a B747 is landing on the downwind runway, a higher crosswind or more lateral runway spacing would be required to protect an aircraft arriving on the parallel upwind runway than if a B737 were landing on the downwind runway.

These two aspects, clustering aircraft with common wake characteristics and being able to determine the transport and decay of wakes as a function of crosswind, could enable the use of this new CSPR arrival procedure.

The following figures illustrate the aircraft separations that could be used on final approach to CSPR using this procedure with two different types of winds. In Figure 6-1, the wind field is consistent at all points along the final approach. WakeVAS determines that wakes from Cluster 1 (current Heavy wake category) and Cluster 3 (B757) aircraft would not be able to transport from the left approach to the right approach path. This allows a 1.5 nmi stagger separation to be used for the trailing aircraft on the right approach rather than a wake separation of 4 nmi. WakeVAS determines that a Cluster 1 wake will transport from the right approach over to the left approach path, so wake separation is required for the following Cluster 3 aircraft.

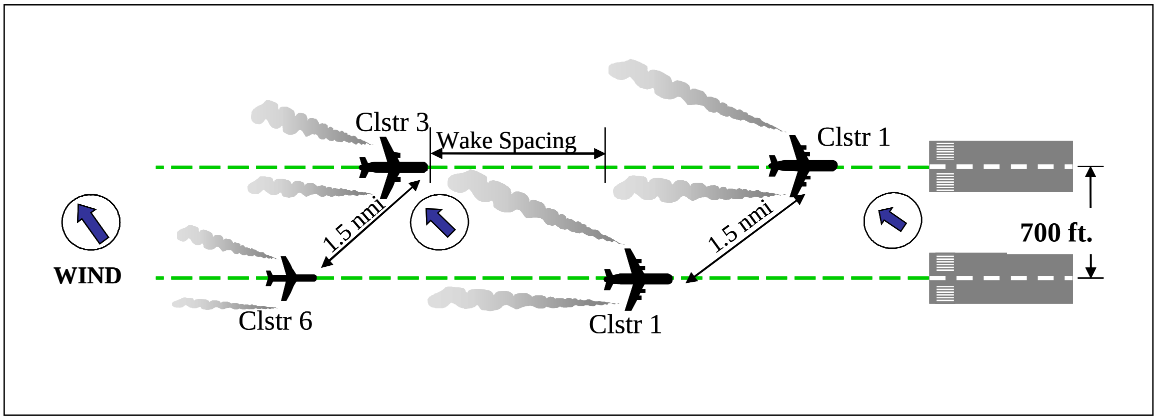

Figure 6-1. Wake Dependency with Consistent Wind Field

The second figure (Figure 6-2) shows a situation where the wind along the final approach varies in direction. In this case, WakeVAS determines that wakes from aircraft in Clusters 1, 2, and 3 can transport between either final approach at some point along final. This situation requires wake separation to be provided behind aircraft in these clusters regardless of which approach the leader is on. In the figure, it appears that the wind would transport the wake from the cluster 3 aircraft away from the right approach, but since the wind field changes on short final, this wake would need to be avoided in that region so wake separation is required behind that aircraft for the entire final approach path.

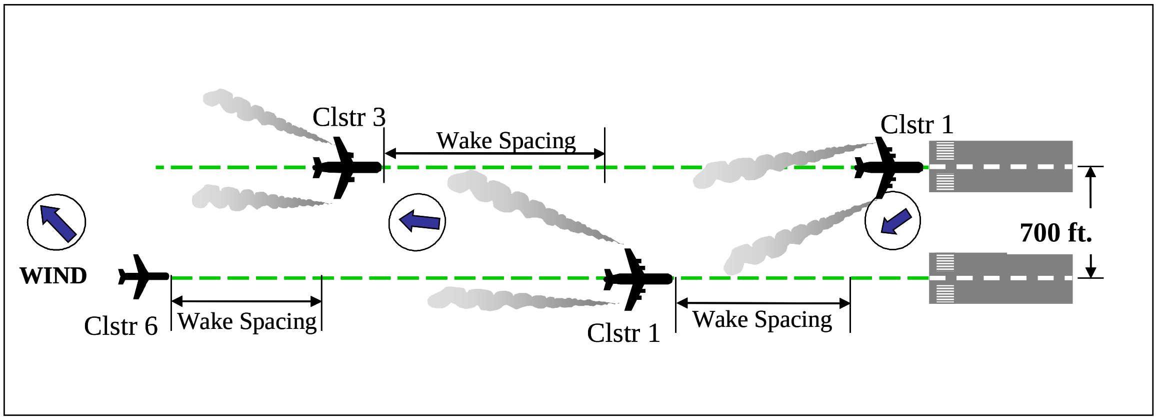

Figure 6-2. Wake Dependency with Inconsistent Wind Field

This procedure will require that statistical data be collected to accurately and reliably describe the wake transport characteristics of wakes generated by aircraft in each cluster for approaches to runways with various centerline spacings. Such statistical data would be used to certify a procedure that specifies the bounds on the maximum lateral transport of wakes under the specified wind conditions for these aircraft clusters. Ultimately a simple table relating winds, aircraft clusters and allowable runway centerline separations would be developed.

This concept is supported by weather data and forecasts to identify the wake dependencies between closely spaced parallel runways and a new decision support tool to assist the controller in identifying those aircraft for which wake separation standards need to be applied.

A system to support this procedure would incorporate the following components:

- Wind measurement sensors and forecast capabilities for about 30 minutes for the approach area out to the region of glideslope intercept. (WakeVAS-Wx1)
- Certified wake data base (i.e., a table) establishing the relationship between weather conditions, runway centerlines and wake hazard existence (yes or no) for aircraft clusters
- A decision support tool capable of using the weather information, the wake data base, and aircraft runway assignments to determine when wake separation is required to separate an aircraft from trailing aircraft approaching the parallel runway
- An interface that would enable the facility (e.g., the supervisor) to determine when the procedure can be run
- A capability to provide wake dependency indications to terminal controllers in aircraft data blocks

Figure 6-3 depicts a high-level block diagram of the major system components and interfaces.

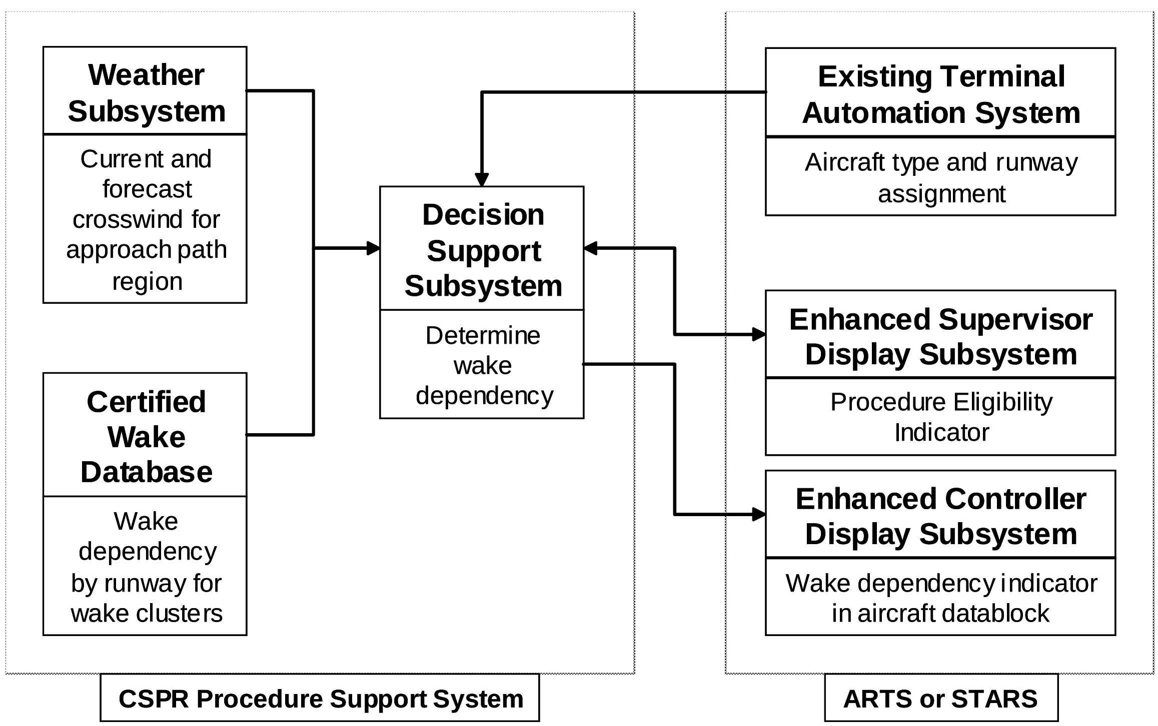

Figure 6-3. System Architecture Components and Interfaces

Two alternatives are presented for implementing the controller interface regarding wake dependency.

In the first alternative, when the aircraft is handed off to the final controller, the runway assignment is assumed to be defined: either by default, by the control symbol for that controller, or as assigned in the data block. Based on this runway assignment, the WakeVAS decision support tool would determine whether wake separation would be required on the parallel final behind this aircraft (see Section 5.2.1 for a discussion of how this determination is made). If so, an indication would be presented to the controller, most likely in the aircraft datablock near the wake class indicator. The South Final controller would need to have his display set to show the datablocks of aircraft arriving the north runway. If one of the north runway arrivals has a wake dependency indicator (perhaps a W in the datablock), then the south final controller would build in wake separation between that aircraft and the next trailing aircraft approaching the south runway. If the north arrival does not display a wake dependency indicator, then the trailing aircraft on the south runway could be spaced as close as a 1.5 nmi stagger from the north aircraft. Of course, in-trail wake separation behind an aircraft ahead on the same final approach would still be required, as in current operations.

The advantage of this case is the simplicity of the wake dependency indication. A disadvantage is that opportunities for more efficient runway assignments may be missed. In addition, issues may arise from a situation where an aircraft controlled by the north final may be switched to a slot on the south final either without a handoff to the south final controller or a change in the runway assignment indicator. In this case, the wake dependency indication could be incorrect. To avoid this situation, aircraft that are swapped to the parallel final would need either to be handed off to that final controller or be so indicated in the data block. This could result in an increase in workload for the controllers over current operations. Flight crews tend to dislike a change in assigned runway during instrument approaches because of the increase in flight deck workload involved in briefing a new approach during a very busy time, so their workload may actually be reduced if fewer runway swaps occur.

The objective of the second alternative is to provide enough information to the feeder and final controllers to allow them to optimize runway assignment based on knowledge of wake dependency. Information would be presented to the feeder and final controllers indicating which one of the following situations exist for an aircraft:

1. Only if the aircraft is assigned to the left runway will wake separation be required between it and a following aircraft approaching the right runway.

2. Only if the aircraft is assigned to the right runway will wake separation be required between it and a following aircraft approaching the left runway.

3. The aircraft can be assigned to either runway and *wake separation will be required* between it and a following aircraft approaching the parallel runway.

4. The aircraft can be assigned to either runway and *no wake separation will be required* between it and a following aircraft approaching the parallel runway.

The advantage to this case is that the controllers are given enough information to enable the most efficient assignment possible consistent with other operational constraints. (i.e., that would result in the fewest instances of wake separation being applied between aircraft that are approaching two parallel runways.) The controllers may not always be able to assign an aircraft to the optimal runway (from a wake perspective) due to other operational considerations, but they will have enough information to assign the optimal runway when possible. A disadvantage to this case is the complexity it may add to the controller interface, controller training, and controller workload due to additional information and relationships that would need to be remembered. If the interface is complex enough, it may have to be embodied into a decision support tool, increasing the cost and development effort for the procedure.

Which of these two options, or further refinements, should be used must be determined through additional analysis of potential benefits and an operational feasibility analysis with controllers.

6.2 Procedure Event Sequence

This section presents event sequences illustrating these two methods for implementing the CSPR Arrival Wake Procedure. Section 6.2.1 uses alternative 1, the simple wake dependency indicator that would only provide the controller with an indication of a wake dependency for the currently assigned runway. No information would be available to the controller on the wake impact of moving the aircraft to the parallel approach. Section 6.2.2 describes event sequences using the more complex wake dependency indicator that provides enough information to the controller to determine if there is a difference in wake dependency (and resulting wake separation) if the aircraft is assigned to one runway or the other. This information would allow the controller to optimize the aircraft runway assignments to result in the fewest possible applications of wake separation, but may require a decision support tool.

6.2.1 Alternative 1: Simple Wake Dependency Indicator

This section describes the sequence of events that would occur using the CSPR Arrival Wake procedure for a hypothetical scenario for two aircraft on approach for Runways 12L and 12R at STL. For emphasis, events unique to the procedure are in italics. Figure 6-4 presents a plan view of the events in relation to aircraft arrival paths.

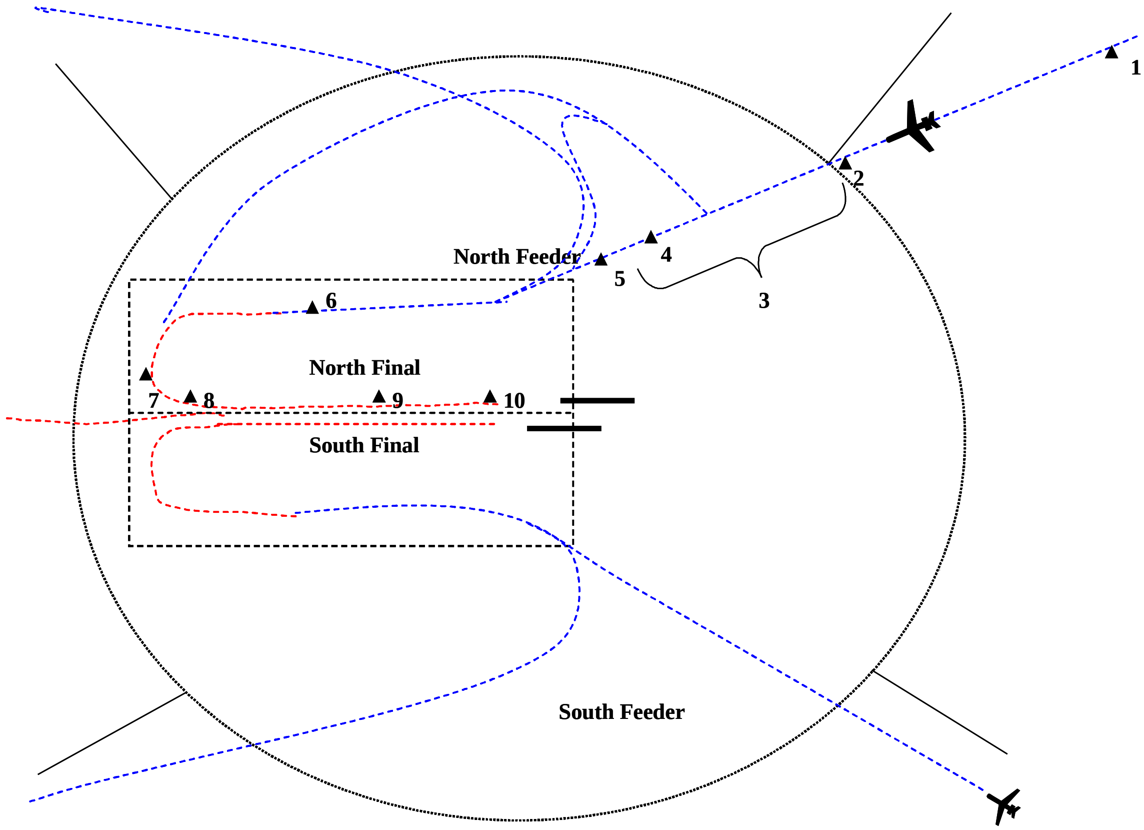

Figure 6-4. Plan View of Event Sequences

In this alternative a wake dependency indicator, W, is used in the lead aircraft's datablock, if wake separation is required between that aircraft and a trailing aircraft approaching the parallel runway. If no wake separation is required for a trailing aircraft on the parallel approach, then no W would be presented in the datablock. In this implementation, the controller would need to scan the datablocks for aircraft approaching the parallel runway for the W indicator and provide wake separation behind those aircraft (see Figure 6-5). A decision support tool would determine the wake dependency based on the runway assignment (either the controller symbol or an assignment in the data block). If the aircraft is switched to the parallel approach, either a handoff or a change in the runway assignment indication would need to occur for the wake indicator to be determined accurately.

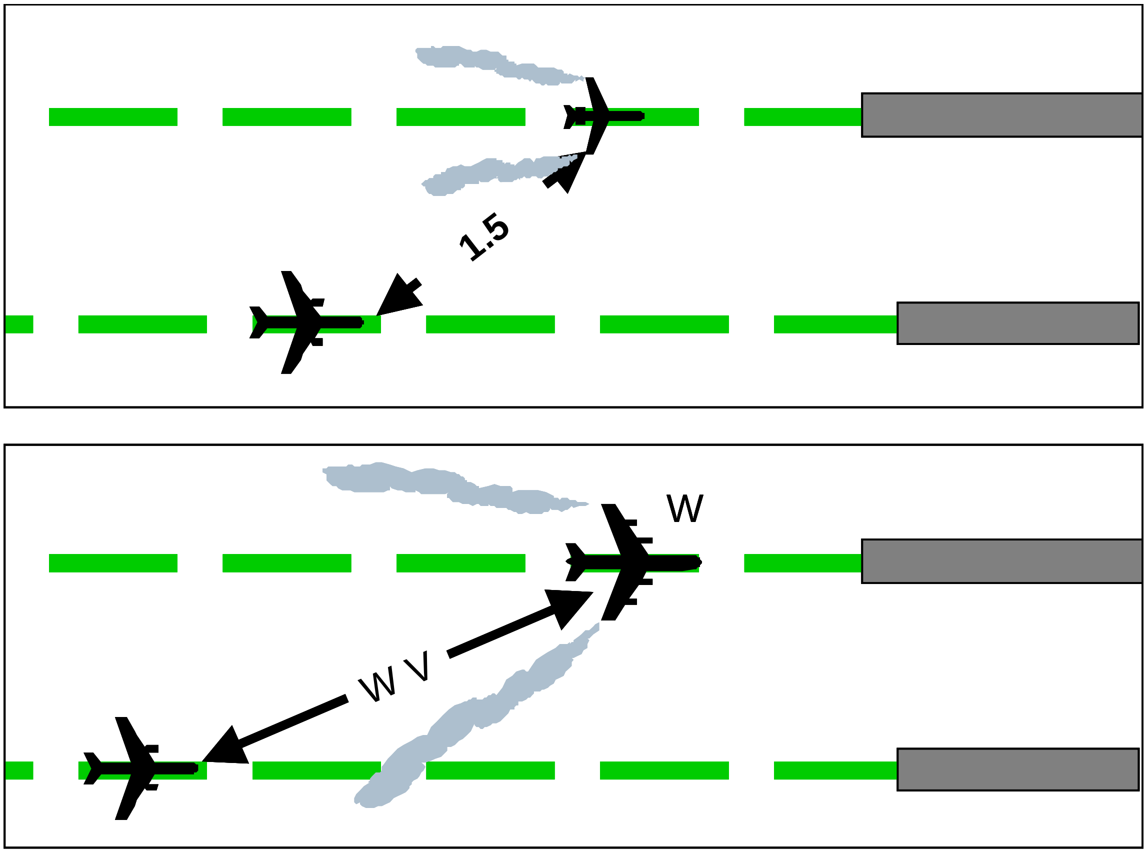

Figure 6-5. Simplified Wake Dependency Indicator

Use of this wake dependency indicator is illustrated through the following event sequence:

1. Enroute initiates handoff

   (a) *Preliminary wind forecast made (30 minute look-ahead), assume forecast reliability is sufficient to avoid fluctuations in dependency indicator*

2. Feeder accepts handoff

   (a) An automation tool determines whether there is a wake dependency or not, based on the runway assignment for the aircraft, wind conditions, and the wake cluster of the aircraft (see Section 5.2.1 and Appendix C). A flag is added to the flight's data block indicating if wake separation will be required between that aircraft and a trailing aircraft on the parallel approach. This flag is shown on the feeder, final and tower controller. Displays

Note that with this procedure in-trail wake separation for approaches to the same runway is the same as current rules. This procedure only affects wake separation for a trailing aircraft on a parallel approach

(b) If wake dependency changes the wake flag in the datablock will flash to alert the controller

3. Resolve conflicts (radar separation)
4. Feeder initiates handoff
5. Final accepts handoff
6. Merge and sequence with traffic
   (a) Own runway traffic (wake separation or radar separation)
   (b) Other runway traffic (wake separation or 1.5 nmi stagger based on wake flag in the leaders datablock)
   (c) Controller takes action, as needed to provide required separation (e.g., speed, vector, turnout, extend downwind, etc.)
7. Establish on localizer
8. Assure separation requirements are met
   (a) A breakout may be required once the aircraft has been established on the ILS if wake dependency status changes and controller can't take action to provide increased separation
9. Handoff to local
10. Clear to land

6.2.2 Alternative 2: A More Informative Wake Indicator

Section 6.2.1 presented a detailed event sequence for the case where the wake dependency indicator presents enough information to the controller to determine when wake separation needs to be applied based on the currently assigned runway (usually the default for the controlling position). This second alternative explores a wake dependency indicator that would provide the controllers with additional information regarding how wake separation requirements will change (or not) if the lead aircraft is assigned to other parallel runway. This would allow the controllers to make decisions regarding more efficient runway assignment for each aircraft to reduce instances where wake dependencies will exist. The implementation scheme uses four wake dependency indicators: L, R, +, -, to indicate when wake separation must be applied to an aircraft trailing on the other parallel runway. The indicators are displayed in the lead aircraft's datablock with the following meanings:

*(L) – An aircraft causes **no wake** dependency for the parallel runway when assigned a **left** runway approach (i.e., that the preferred assignment is left runway)*

*(R) – An aircraft causes **no wake** dependency for the parallel runway when assigned a **right** runway approach ((i.e., that the preferred assignment is right runway)*

*(+) – An aircraft causes **no wake** dependency for the parallel runway when assigned **either** runway approach*

*(–) – An aircraft causes **wake** dependency for the parallel runway when assigned **either** runway approach*

Based on the wake indicator, one of two cases exist:

Case 1: If the wake flag matches the runway assignment or is a "+" there is no wake impact on the parallel trailer aircraft (see Figure 6-6).

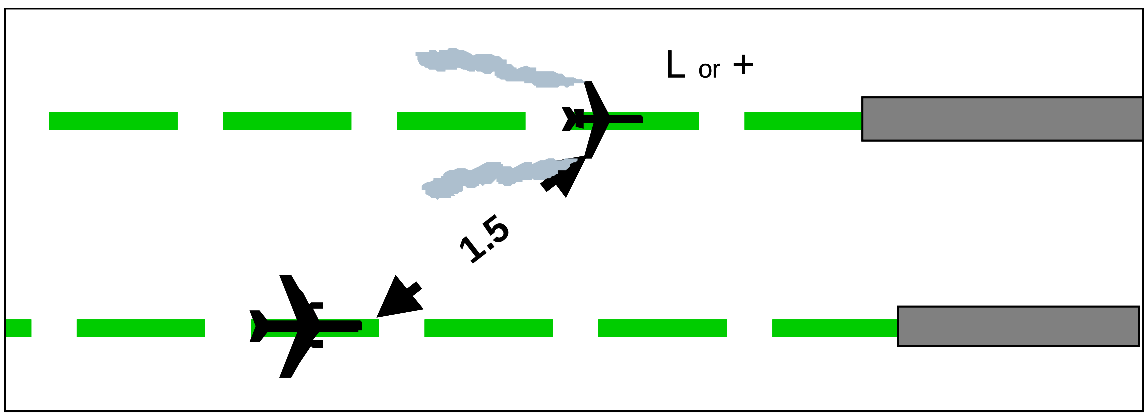

Figure 6-6. Example of No Wake Dependency

Case 2: For all situations other than Case 1, there is a wake impact on the trailing aircraft landing on the parallel runway (see Figure 6-7).

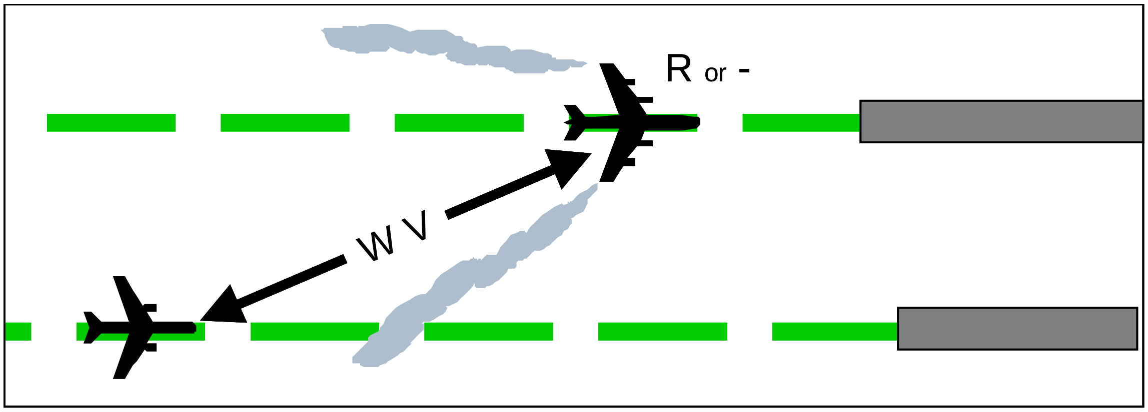

Figure 6-7. Wake Dependency Example

To illustrate how this wake indicator would be used to optimize runway assignment, consider the North Feeder controller accepting a handoff for AAL123. Based on the current and forecast wind conditions (cross wind from the north) and the wake class of AAL123, the decision support tool determines that if this aircraft is assigned to Runway 12L (the default for the North Feeder) then wake separation will be required for a trailing aircraft approaching Runway 12R. If, on the other hand, AAL123 is assigned to Runway 12R, the north crosswind will transport its wake away from the approach to Runway 12L and no wake separation would be required for a trailer approaching Runway 12L. The decision support tool would indicate this situation by placing an R in the datablock for AAL123. If the traffic situation and facility procedures permit, the North Feeder controller could plan on feeding AAL123 to Runway 12R and cross the aircraft over and handoff to the South Final controller. This action would result in saving an arrival slot that would have otherwise been skipped and used to apply wake separation.

If there is an aircraft to be merged into a "hole" in the arrival stream for one runway, then both the merging aircraft's leader and follower relationship need be considered when determining the size of the "hole" that is required.

6.3 Operational Use Scenario

The following scenario provides an example of how the procedure described in Section 6.2.2 would be used in a situation where a leading aircraft is arriving on the 12L runway at Lambert-St. Louis International Airport. Wake vortex separation (Figure 6-8) will be applied behind that aircraft when its datablock displays either an (R) or (–) symbol. In this scenario, American Airlines 717 is a heavy jet (Boeing 777) bound for ILS Runway 12L. It is followed by Continental 888, a large jet (Boeing 737) bound for ILS Runway 12R.

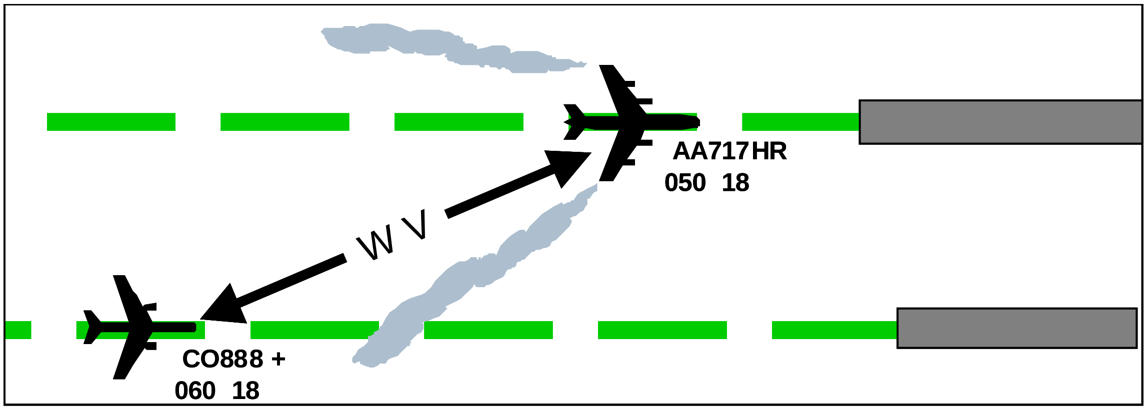

Figure 6-8. Wake Separation on Final Approach for Scenario Aircraft

The scenario starts as the two flights are handed off to approach control.

Step 1 in the Event Sequence

ARTCC Low Altitude Sector controller: "American 717 Heavy contact St. Louis Approach on 131.7." (The center controller has flashed the handoff and the St. Louis approach controller has accepted the handoff.)

Step 2 in the Event Sequence

American 717: ".7"

American 717: "St. Louis, American 717 Heavy with Lima, with you."

St. Louis North Feeder: "American 717 Heavy radar contact 37 miles Northeast of St. Louis squawk 2737 expect ILS 12 Left approach, fly heading 280."

Step 3 in the Event Sequence –Feeder Controller makes decision for runway assignment based on automation data block and current traffic load. The wake flag, R, in the datablock indicates that if the aircraft is assigned to 12R there will be no wake separation required for a trailer on 12L. Due to traffic constraints, the controller assigns AAL 717 to 12L even though the wake separation applied to a trailer on 12R will cause an arrival slot to be lost.

American 717: "Roger 280."

Step 1 in the Event Sequence

ARTCC Low Altitude Sector controller: "Continental 888 contact St. Louis Approach on 131.8." (The center controller has flashed the handoff and the St. Louis approach controller has accepted the handoff.)

Step 2 in the Event Sequence

Continental 888: “.8”

Continental 888: “St, Louis, Continental 888 with Lima, with you.”

St. Louis South Feeder: “Continental 888 radar contact 33 miles Southeast of St. Louis squawk 2755 expect ILS 12 Right approach, fly heading 260.”

Step 3 in the Event Sequence –Approach Controller makes decision for runway direction based on automation data block and current traffic load. In this case the wake flag, +, indicates that the aircraft can be assigned to either runway without incurring a wake separation penalty for a trailer on the parallel runway.

Continental 888: “Roger 260.”

St. Louis North Feeder: “American 717 Heavy descend and maintain 10 thousand.”

American 717 Heavy: “Roger, American 717 Heavy out of 15 thousand for 10 thousand.”

Step 4 in the Event Sequence

St. Louis South Feeder: “Continental 888 descend and maintain 9er thousand.”

Continental 888: “Roger, Continental 888 out of 14 thousand for 9er thousand.”

St. Louis North Feeder: “American 717 Heavy Turn Right heading 300 descend and maintain 7 thousand, contact St. Louis Final on 130.9, good day.” (St. Louis Final controller has accepted the handoff on American 717 Heavy.)

Step 5 in the Event Sequence

American 717 Heavy: “Roger, 300 down to 7, St. Louis on .9”

American 717 Heavy: “St. Louis, American 717 Heavy with you.”

St. Louis North Final: “American 717 Heavy radar contact 10 miles north of St. Louis, fly heading 300 descend and maintain 5 thousand.”

Step 6 in the Event Sequence

American 717 Heavy: “Roger, 300 out of 7 for 5.”

Step 7 in the Event Sequence

St. Louis South Feeder: “Continental 888 Turn Right heading 300 descend and maintain 6 thousand, contact St. Louis Final on 130.8, good day.” (St. Louis Final controller has accepted the handoff on Continental 888.)

Step 6 in the Event Sequence

Continental 888: "Roger, 300 out of 9er for 6 St. Louis on .8."

Continental 888: "St. Louis, Continental 888 with you."

St. Louis South Final Control: "Continental 888 radar contact 12 miles south southeast of St. Louis fly heading 300 maintain 6 thousand."

St. Louis North Final Control: "American 717 Heavy Turn Left heading 180."

Step 7 in the Event Sequence

American 717 Heavy: "Roger left to 180."

St. Louis North Final Control: "American 717 Heavy continue left to 120 cleared ILS Runway 12 Left approach, traffic twelve o'clock 4 miles westbound, Boeing 737."

Step 8 in the Event Sequence – Final Controller makes assessment based on data block flag and establishes on localizer based on Wake Vortex separation rules.

American 717 Heavy: "Roger cleared ILS Runway 12 Left approach, Tally on the traffic."

St. Louis South Final Controller: "Continental 888 turn right heading 020."

Continental 888: "Roger right to 020."

St. Louis North Final Controller: "American 717 Heavy contact tower on 129.1, good day."

Step 10 in the Event Sequence

American 717 Heavy: "Roger tower on 129.1, see you."

St. Louis South Final Control: "Continental 888 turn right 120 cleared ILS Runway 12 Right approach, traffic twelve o'clock 5 miles for 12 Left, Boeing 777."

Step 8 in the Event Sequence – Final Controller makes assessment based on data block flag and establishes on localizer based on Wake Vortex separation rules.

Continental 888: "Roger traffic, 888 is cleared for the ILS 12 Right approach."

American 717 Heavy: "St. Louis, American 717 Heavy with you."

St. Louis Tower Local Control: "American 717 Heavy cleared to land Runway 12 Left, check gear down, wind 090 at 12."

Step 12 in the Event Sequence

American 717 Heavy: “Roger cleared to land 12 Left, gear down.”

St. Louis South Final Control: “Continental 888 contact tower on 129.1, good day.”

Step 10 in the Event Sequence

Continental 888: “Roger tower on 129.1.”

Continental 888: “St. Louis, Continental 888 with you.”

St. Louis Tower Local Control: “Continental 888 cleared to land Runway 12 Right, check gear down, wind 080 at 8.”

Step 12 in the Event Sequence

6.4 Relationship to Government and Industry Concepts

The CSPR Arrival Wake Procedure described in this section is consistent with [26]. This procedure addresses the following capabilities of the mid-term arrival/departure environment described in the RTCA Conops.

- “Modifications to service provider procedures and the improvements in turbulence and wake vortex avoidance to facilitate a reduction in separation standards.”
- “Service providers use DSSs to provide a consistent level of service (throughput) under the same conditions over time to optimize the use of airport capacity, considering aircraft types, weather, and winds aloft.”
- “Other capabilities generate advisories to the service provider that aid in maneuvering flights into final approach in accordance with the planned traffic sequence and dynamic vortex separation.”

While this CSPR Arrival Wake Procedure is beyond the timeframe addressed by the FAA’s *Operational Evolution Plan*, it is consistent with and builds upon the existing programs to safely improve airport arrival/departure rate.

Section 7

Conclusions and Next Steps

NASA's WakeVAS program is designed to develop capabilities that will provide benefits to the NAS by reducing or eliminating specific wake vortex related limitations in the system. To this end, the WakeVAS program will develop technologies that could be applied in the NAS. These benefits can only be realized by the FAA in the context of specific procedures that it can evaluate, certify and authorize as safe and feasible. In these evaluations, the technological aspects form only one portion of the set of considerations. The specific ATC procedures that would utilize the proposed technologies imply a set of other considerations vital to the FAA and other stake-holders. These latter considerations imply specific development considerations for the proposed procedures. The capabilities to be developed must provide a reasonable balance of expected benefits and expected development risks. Such tradeoffs can be compared in the context of potential ATC procedures utilizing the proposed WakeVAS technologies.

This document showed that many candidate procedures that would utilize proposed WakeVAS technologies are possible, and that the spectrum of potential procedures becomes even greater when other enabling or enhancing technologies are considered. It presented an overview of the technologies that could be applied to ATC wake procedures and explored many options for how information made available by these technologies could be leveraged to provide step-wise options for modifying current arrival and departure procedures.

This document presented preliminary high level description of potential procedures, provided an example of a more detailed analysis of a smaller set of procedures, and a methodology for simulating potential capacity increases and realistically assessing the benefit to individual airport operations. A separate briefing presented the numerical benefit results derived for the candidate procedures as well as some of the issues that must be addressed.

The ATC procedures analyzed in this investigation should be considered at the stage of concept exploration. Any procedures that show benefits will need to be evaluated further by NASA, FAA and the stakeholders with respect to development and implementation risks prior to being recommended for development.

The data used for prototyping this procedure assessment and capacity simulation methodology was based on a preliminary estimate of values for AVOSS input parameters. The resulting AVOSS output data was sufficient to validate the methodology described in this document, but the actual capacity results may vary based on the parameter values used. The issues encountered during the analysis indicate that a specific activity to benchmark AVOSS output for use in operational benefit computations would be beneficial. In particular, a consistent relationship between the AVOSS decay, sink, and transport results and current in-trail wake separation standards could not be developed for use in modeling single runway arrival and departure capacity. Once such a benchmarking activity is conducted, appropriate AVOSS output could be used with the methodology described in this document to compute numerical benefit estimates for candidate procedures.

The following steps are recommended to take this analysis to the next level.

- Conduct the necessary development and coordination to establish a relationship between AVOSS numerical output and current ATC separation standards.
- Once the correspondence with current operational standards is established, run AVOSS for environmental parameters of interest, including parameters based on knowledge gained through prototyping the capacity simulation process.
- Based on this output, analyze a sub-set of candidate procedures for potential operational benefits.
- Analyze the candidate set of procedures for operational issues (e.g., controller, flight crew) and resolve/mitigate accordingly.
- Analyze the candidate set of procedures for development and deployment risk.
- Based on a trade-off between the computed benefits and the development and deployment risk, recommend a set of candidate procedures for further development by the WakeVAS program.

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Appendix A

Detailed Descriptions of Potential Arrival and Departure Procedures

This section explores options for applying WakeVAS and other potential technologies to achieve capacity and safety benefits. The options are arranged into tracks showing an incremental evolution of a particular procedure as various technologies mature and can be applied to achieve some level of additional benefit in each step. Each track begins where the current FAA wake program leaves off and explores additional operational benefits that could possibly be derived from application of WakeVAS technologies. The starting point for single runway arrival and departure procedures is the current rules in FAA Order 7110.65. For arrivals to CSPR, the base procedure is the FAA near-term proposal for a revised 2500 feet rule based on the wake class of lead aircraft, applicable for all weather conditions. For departures from CSPR, the base procedure is the FAA mid-term proposal for a revised 2500 feet rule based on winds.

A.1 WakeVAS Technology Applications for CSPR Arrival Procedures

The first set of applications investigated was the application of WakeVAS technologies to arrival operations at airports with closely spaced parallel runways. Figure A-1 shows an overview of the arrival evolution options considered starting with the base procedures on the left, corresponding to the near-term timeframe, and progressing in time toward the right. Technology required for each step is shown at the bottom of the figure. Technology required for more advanced steps (in time) will require the accumulated technology required in previous steps of that same track.

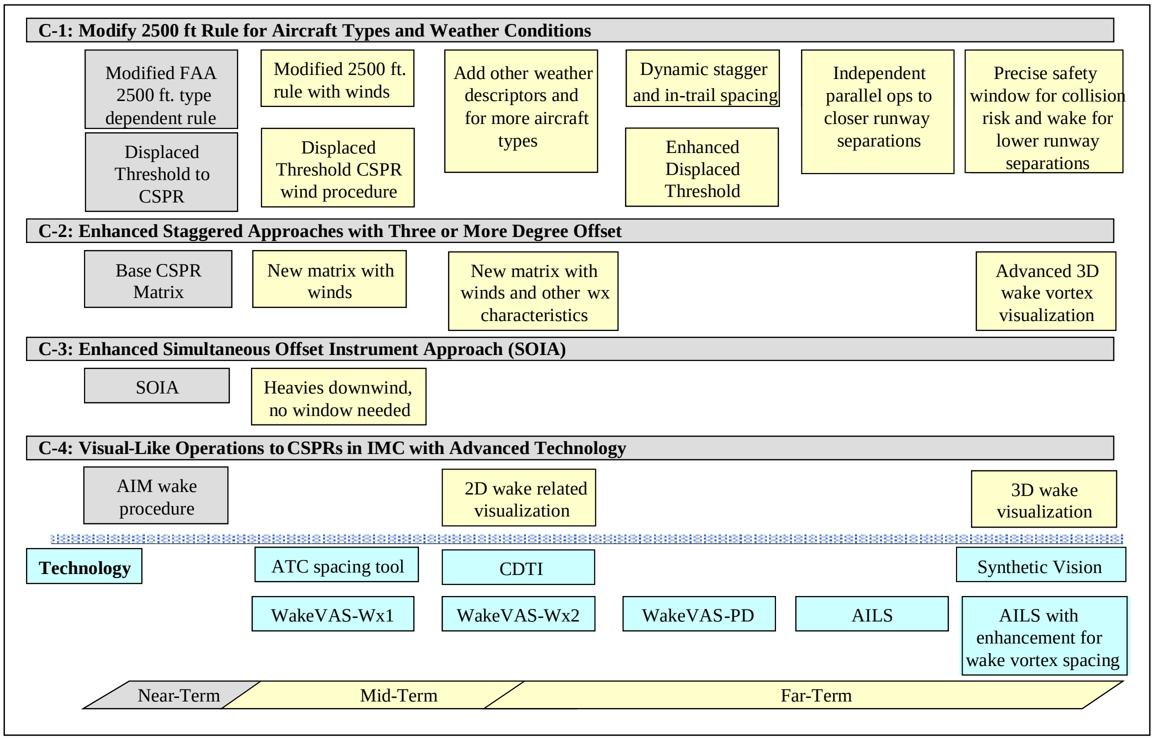
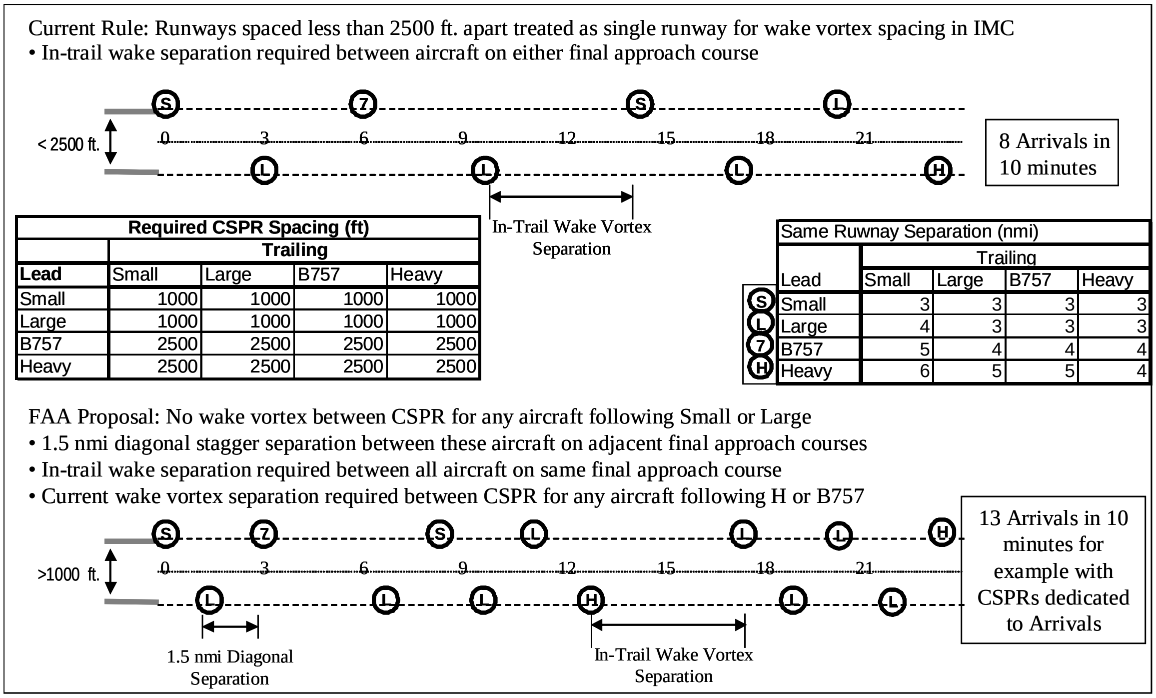


Figure A-1. CSPR Arrival Evolution Options

A.1.1 Track C-1: Modify 2500 feet Rule for Aircraft Types and Weather Conditions

The potential procedures in this track could provide benefit during marginal VMC and IMC weather conditions.

The base procedure for track C-1 is the FAA near-term modification of the 2500 feet minimum lateral spacing rule for wake vortex dependency for arrivals to CSPR. For this procedure (see Figure A-2) runways with at least 1000 feet parallel runway spacing would not be considered CSPR for an aircraft pair when Small or Large wake class aircraft are leading. All other arrival cases would require the current 2500 feet lateral runway spacing to not be considered CSPR.



Required CSPR Spacing (ft)				
	Trailing			
Lead	Small	Large	B757	Heavy
Small	1000	1000	1000	1000
Large	1000	1000	1000	1000
B757	2500	2500	2500	2500
Heavy	2500	2500	2500	2500

Same Ruwnay Separation (nmi)				
	Trailing			
Lead	Small	Large	B757	Heavy
Small	3	3	3	3
Large	4	3	3	3
B757	5	4	4	4
Heavy	6	5	5	4

Figure A-2. FAA Proposed Near-Term Procedure

The first enhancement in Track C-1 could use WakeVAS wind information in the mid-term timeframe to determine when wakes will be transported clear of the CSPR. The upwind and downwind runways are considered separately for each wind case and lead aircraft wake class. Data will be collected over an extended time period documenting when each wind condition reliably transports the wake of certain class aircraft such that the wake is no factor for arrivals to the parallel runway. This historical data can then be used to establish an arrival procedure that can eliminate wake dependencies when appropriate. Displaced thresholds may also be used to advantage to provide vertical separation between aircraft approach paths. In principle, at this stage, the WakeVAS program could provide a generalized table or algorithm showing required aircraft stagger separations as a function of runway separation, winds and runway threshold displacement.

The second enhancement could be to include WakeVAS turbulence and other weather descriptors in the mid to far-term to determine cases when wakes will decay and not be a factor to aircraft approaching the parallel runway. The knowledge of EDR and other weather factors and their effect on the time for a wake to decay to background turbulence level, combined with the knowledge of wake transport behavior, may provide other opportunities to safely lower runway spacing requirements. More combinations of lead and trail aircraft type may be included when the impact of weather conditions on wakes are considered.

Also in the far-term, active wake prediction and detection may enable the third enhancement to allow dynamic stagger and in-trail spacing values as well as opportunities to use CSPR with less displacement between their runway thresholds. This enhancement would include the establishment of a new reduced standard for dependent parallel operations (possibly less than 1.5 nmi stagger in IMC) for runways spaced closer than 2500 feet, and the application of enhancements possible in single runway separations through WakeVAS-PD described in Track A-3.

The fourth enhancement would take advantage of AILS to enable independent parallel operations between CSPR closer than 2500 feet (AILS is currently limited to 2500 feet runway separations.) The fifth enhancement uses an enhanced tool to use a dynamically determined safety window for lower runway spacings, protecting aircraft against both collision risk and providing separation from wake vortices. Both of these ADS-B based enhancements would be in the far-term timeframe.

A.1.2 Track C-2: Enhanced Staggered Approaches with Three Degree of More Offset

The second track may provide benefit to CSPR arrival operations during marginal VMC conditions.

The base procedure for this track is to establish an approach to one or both parallel runways where the approach course is offset by three degrees (away from the parallel approach course) in order to maintain at least 2500 feet lateral spacing between flight paths until closer to the threshold and lower on the glideslope. (see Figure A-3) Aircraft on the offset approach will be paired with a leader on the straight-in approach to the other parallel runway. The flight crew will acquire the leader and accept visual separation prior to a decision point. An example of a possible spacing matrix is shown in Tables A-1 and A-2, depending on whether the runway thresholds are staggered more than 1000 feet or not. See [27] for more information on this procedure.

Such a procedure is not currently in operation nor is it being developed; it is being proposed here as a potential procedure based largely on current rules.

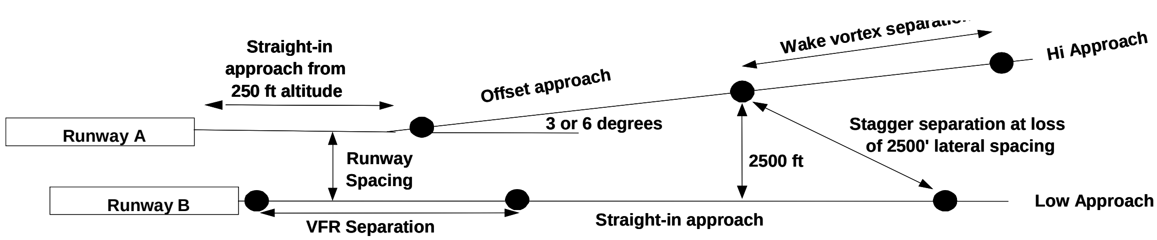


Figure A-3. Three Degree Offset Approach

Table A-1. Base CSPR Matrix with Runway Stagger <1000 feet

CSPR Adjacent In-Trail Spacing (nmi.): Procedure 2A				
	Trailing			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
L:low approach	1.5	1.5	1.5	1.5
L:high approach	1.5	1.5	1.5	1.5
Heavy/757: low approach	wv	wv	wv	wv
Heavy/757: high approach	wv	wv	wv	wv

Table A-2. Base CSPR Matrix with Runway Stagger >1000 feet

CSPR Adjacent In-Trail Spacing (nmi.): Procedure 2B				
	Trailing			
Leading	Small	Large	B757	Heavy
Small	1.5	1.5	1.5	1.5
L:low approach	1.5	1.5	1.5	1.5
L:high approach	2.5	2.5	2.5	2.5
Heavy/757: low approach	wv	wv	wv	wv
Heavy/757: high approach	wv	wv	wv	wv

The first enhancement could use WakeVAS wind information in the mid-term timeframe to determine when conditions will allow reduced wake separations based on runway spacing and aircraft type. This may allow lower ceiling requirements for the approach since aircraft can proceed to closer than 2500 feet before acquiring traffic visually.

The second enhancement for this track could use turbulence and other WakeVAS weather information in the mid-term to far-term timeframe to identify additional opportunities when wake separation can be safely reduced.

Advanced three-dimensional wake vortex visualization using synthetic vision technology in the far-term could provide a third enhancement enabling the pilot to visualize the modeled position of wakes from the leading aircraft providing the equivalent of visual separation from wakes in marginal VMC weather conditions.

A.1.3 Track C-3: Enhanced Simultaneous Offset Instrument Approach (SOIA)

This track could provide benefit to CSPR arrival operations during marginal VMC conditions in the mid-term timeframe.

The basic SOIA provides an approach to one runway that has a parallel offset to maintain 3000 feet lateral spacing (see Figure A-4). A sidestep maneuver is used to join the final approach course aligned with the runway. The flight crew acquires traffic and accepts visual separation for collision avoidance from other aircraft prior to the sidestep. For wake turbulence protection, however, this procedure may require spacing windows between certain pairs of aircraft for certain airport implementations.

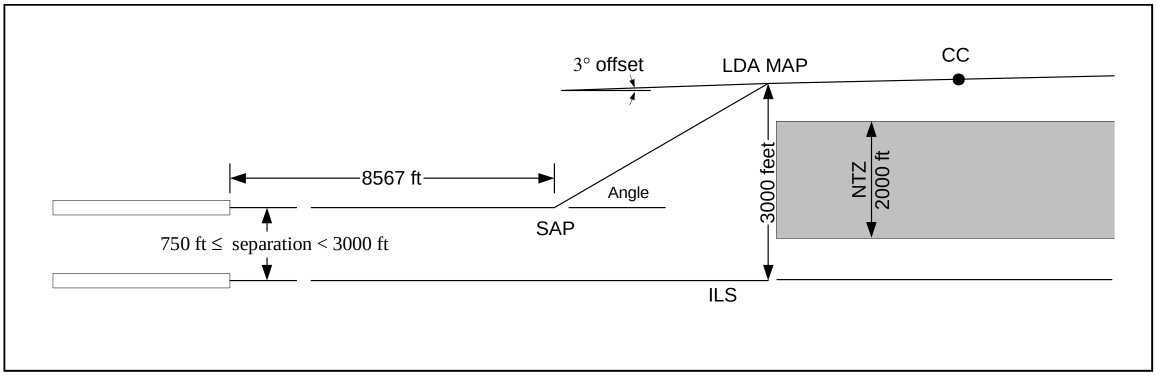


Figure A-4. Simultaneous Offset Instrument Approach Geometry

For more information on SOIA, see FAA Order 8260.49.

An enhancement to the base SOIA procedure could be achieved with WakeVAS wind information in the mid-term timeframe. Based on extensive data collection on wake movement for different wind conditions, some of the restrictions on pairing aircraft for SOIA approaches by type at certain airports could be relaxed dynamically. Specifically, if data observations show that for certain wind conditions wakes generated by Heavy aircraft approaching the downwind runway cannot reach the upwind approach, then the spacing window could be eliminated for those cases, reducing controller workload and improving the capacity benefit.

A.1.4 Track C-4: Visual-like Operations to CSPR in IMC with Advanced Technology

The base procedure for this track is the wake avoidance procedure for pilots described in the AIM. The procedure relies on the pilot's visual observation of the aircraft generating the wake and the pilot's estimate of where that wake would exist behind the generating aircraft. This estimate is based on the wake sinking below the generator's flight path (if out of ground effect) and transporting laterally with the wind.

The first enhancement for visual-like operations with WakeVAS may be to place cues on a CDTI that would indicate the own ship position with respect to leading aircraft approaching a parallel runway. This would aid in vertical positioning to stay above the glide path of the leading aircraft for wake avoidance. In conjunction with C-EFR, this may provide some capacity gains in visual conditions. This capability could perhaps be certified in the far-term to safely enable closer separations from wakes based on real-time knowledge of wake transport and decay.

Also in the far-term, synthetic vision technology could provide a three-dimensional visualization to pilots showing wakes from other aircraft (as well as positions of other aircraft) with the intent to certify this tool for use in visual-like operations.

A.2 WakeVAS Technology Applications for Arrivals to a Single Runway

The second set of applications investigated was the application of WakeVAS technologies for arrival operations to single runways. Figure A-5 shows an overview of the arrival evolution options considered, starting with base procedures on the left, corresponding to the near-term timeframe, and progressing in time toward the right. Again, the technology required for each step is shown at the bottom of the figure. Technology required for more advanced steps (in time) will require the accumulated technology required in previous steps of that same track. Each of the four tracks are discussed in detail below.

All enhancements in this set apply when visual approaches can not be conducted, i.e., in IMC and marginal VMC.

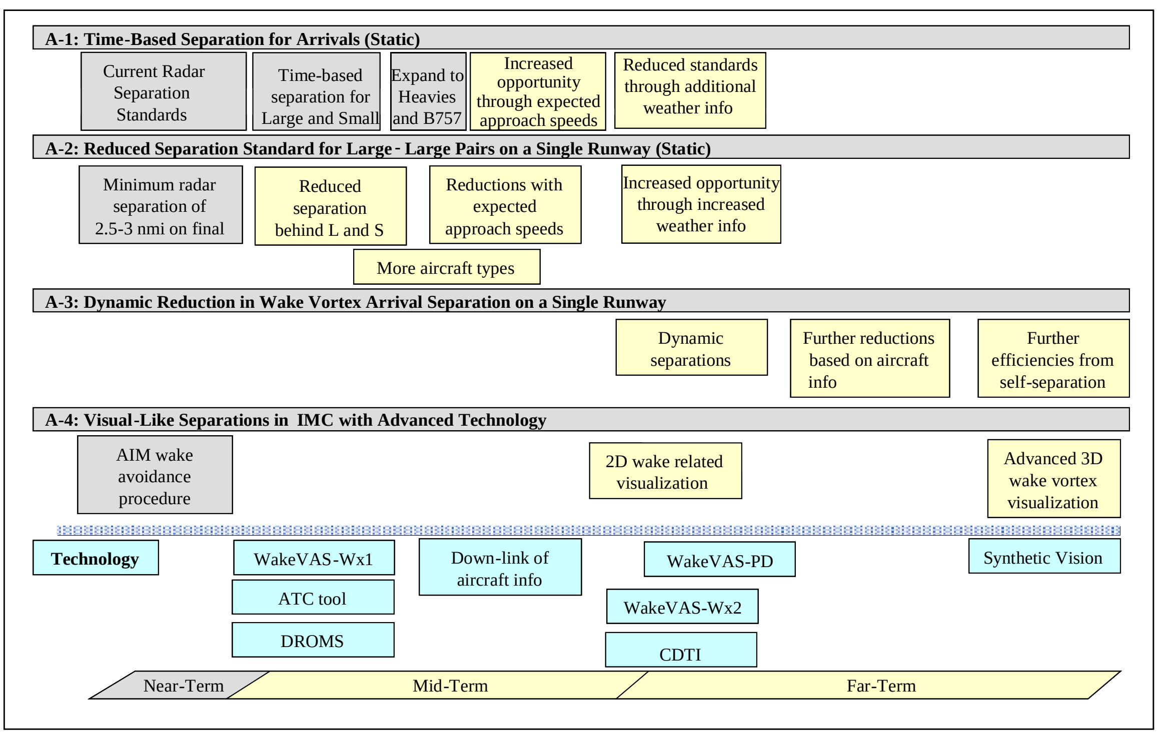


Figure A-5. Single Runway Arrival Evolution Options

A.2.1 Track A-1: Time-based Separation for Arrivals (Static)

The base procedure for this track utilizes time based standards for approach separations. Operational experience indicates that acceptance rates at airports drop significantly during high headwind conditions. This is ultimately because aircraft speeds over ground are reduced during high headwind conditions.[20] If time based separations were utilized, these changes in acceptance rates could be reduced or eliminated. The procedure converts time based standards into distance values, to be used by controllers with the help of an approach spacing tool. The time values as well as the resulting fractional distance values would thus be transparent to controllers.

For more information on the proposed procedure, see [27]. This procedure is not in operational use anywhere at this time, but is being pursued in Europe for development.

The enhancement for Track A-1 would take advantage of WakeVAS winds, turbulence and other weather information to identify periods when wake transport or decay would be accelerated and allow reductions in in-trail time separations.

A.2.2 Track A-2: Reduced Separation Standard for Certain Pairs on a Single Runway (Static)

This proposed procedure would allow a two nmi separation between certain combinations of aircraft pairs under some weather conditions. There are seven weight class pairs considered for modification in this procedure.

The base procedure for this track is the standard practice of maintaining a radar separation of 2.5 nmi within 10 nmi of the threshold if the weight class of the leading aircraft is not larger than that of the trailing aircraft, given an average runway occupancy time of 50 seconds. Heavy aircraft and B757s are only permitted to participate as the trailing aircraft, and certain other restrictions apply. Table A-3 lists the combinations of lead and trail aircraft types that can participate.

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[20] in spite of the fact that most aircraft utilize some increment of speed with winds

Table A-3. Participating Aircraft Weight Class Pairs

Leading Aircraft Weight Class	Trailing Aircraft Weight Class
Small	Small
Small	Large
Small	B757
Small	Heavy
Large	Large
Large	B757
Large	Heavy

The first enhancement to this procedure would be to allow a reduction from 2.5 to 2.0 nmi within 10 nmi of the threshold for the same pairs of aircraft that qualify for the base procedure. Before the current separation standard can be reduced to 2 nmi, two factors must be resolved:

- ensuring a clear runway for the landing of the trailing aircraft, given a runway occupancy time and a safety buffer
- ensuring that the wake of the leading aircraft does not affect the trailing aircraft, along the entire final approach segment, given the minimum separation distance

Based on data collected over all relevant conditions, a maximum observed wake vortex residence time for wakes of significant strength would be established for the aircraft pairs considered in this analysis for each crosswind value. WakeVAS wind data would then be used to determine current and near-term crosswind forecast. When the forecast crosswind value exceeds a minimum threshold, the lower two nmi separation would be used.

WakeVAS predictive capabilities will provide the required wind forecast along the approach path. The minimum prediction time must cover the time period for the final approach, although additional study is needed to assess whether this capability is sufficient. A wind forecast along the final approach path for about ten minutes in future may therefore prove to be adequate for this application. It is unlikely that the airport acceptance rate would be adjusted based on the use of this procedure unless a reliable wind forecast could be made for at least 30 minutes into the future. Even if acceptance rates were not adjusted, operational benefits, including decreased flight times for arrivals, could be expected. Further investigation is required for issues surrounding transitioning into and out of time periods when reduced separation can be used.

The second enhancement for Track A-2 allows B757 and Heavy aircraft to participate as lead aircraft when an ATC spacing tool is introduced. Such a proliferation of separation values could only be accommodated through a spacing tool. The spacing tool will reduce controller workload and help to guarantee that the correct spacing is used behind aircraft.

The third enhancement for Track A-2 allows further reductions in in-trail spacing based on the aircraft down-link of final approach speed to ground automation. The reduced standard in the previous enhancements in this track assumed that the trailing aircraft had a landing speed of (say) 150 kts, as a worst case. If the actual landing speed were known, a further reduction in the spacing required to exceed a specific wake residency time (plus safety buffer) could be achieved.

The effective time separation for the 2.0 nmi separation may be presented as a two-dimensional contour map. On Figure A-6, the contour lines of equal effective time spacing for a 2.5 nmi distance spacing appear in gray, dashed lines; the contour lines for equal effective time spacing for a 2 nmi distance spacing appear in black, solid lines. The horizontal axis portrays the range in approach speed of the trailing aircraft from 110 to 150 kts; the vertical axis portrays the range of headwind speed from 0 to 30 kts. This contour map is based on the assumption that an aircraft will maintain the same Indicated Airspeed at landing for different levels of headwind, which should be validated during further development of this procedure.

In Figure A-6, Point A is located where a 60-second time spacing is required to maintain a 2.5 nmi distance spacing if the speed of the trailing aircraft is 150 kts, in the absence of a headwind. Given a 30 kt headwind (Point A'), the same effective time separation of 60 seconds is obtained if the distance is reduced to 2 nmi, assuming a speed of 150 kts for the trailing aircraft.

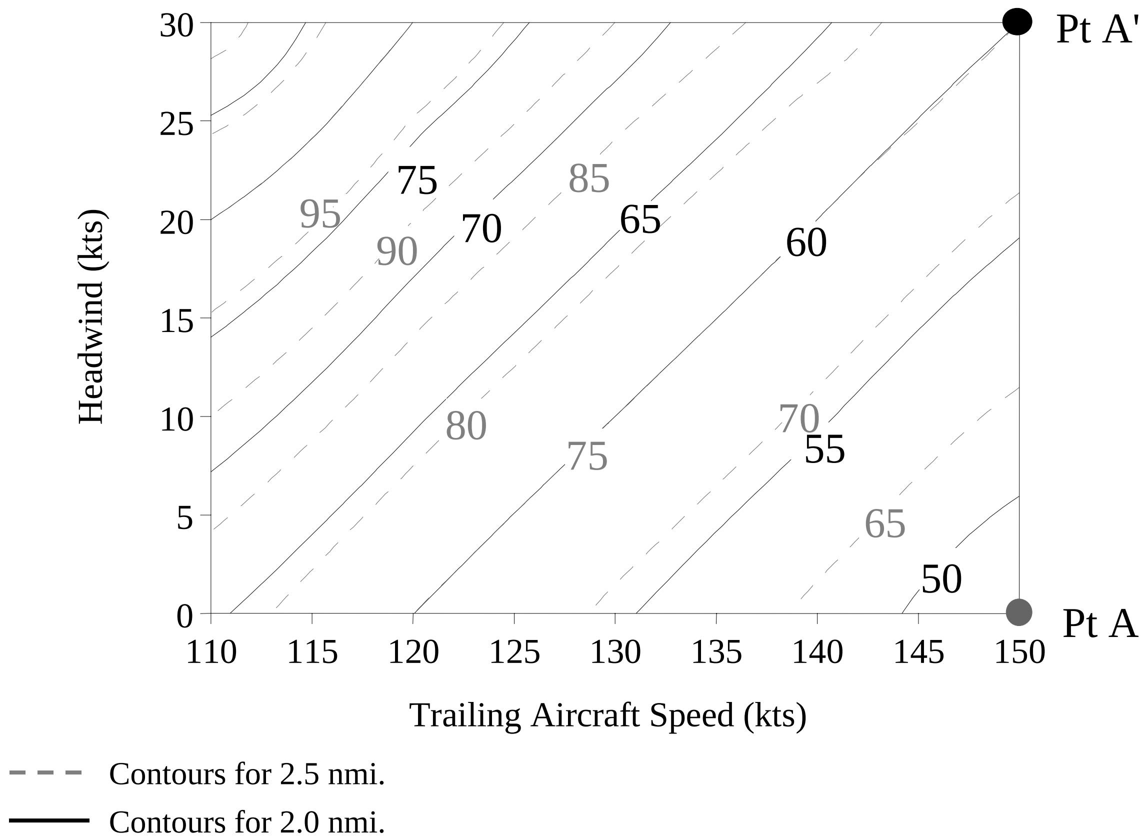

Figure A-6. Contours of Effective Time Separation as a Function of Headwind, Trailing Aircraft Speed, and Separation Distance

The benefit derived from adopting the reduced separation standards assumes that the wake created by the landing aircraft will not impact the next aircraft arriving at the runway threshold. The absence of the wake created by the leading aircraft may be due to the combined effects of wake transport by a crosswind (as used in Track A-2 enhancements one through three) and wake dissipation due to turbulence. Enhancement four utilizes WakeVAS turbulence and weather information to identify additional opportunities for spacing reductions during periods when the EDR will lead to accelerated decay of wakes. This accelerated decay will further reduce wake residency times and result in less in-trail spacing to insure the trailing aircraft does not cross the landing threshold until the leader’s wake has either transported clear of the approach path or decayed to the level of background turbulence.

A.2.3 Track A-3: Dynamic Reduction in Wake Vortex Arrival Separation on a Single Runway

Track A-3 picks up where Tracks A-1 and A-2 leave off, thus the final enhancements in Tracks A-1 and A-2 represent the base procedure for Track A-3.

The first enhancement in this track is through the use of WakeVAS weather information and active wake detection and prediction. These capabilities will enable dynamic determination of minimum safe wake vortex spacings for each trailing aircraft on final approach. Rather than being based only on historical wake observations, this enhancement will incorporate prediction of wake decay, sink and transport based on WakeVAS weather sensors and the weather and wake prediction algorithm. The wake behavior predicted by WakeVAS will be constantly checked for accuracy through the use of ground-based active wake detection sensors. If the measured wake location or strength is trending away from the predicted wake values, then a transition out of this procedure should be initiated. The bound on the difference between the predicted and actual wake behavior must be sufficiently small that it will allow time for aircraft already on approach to complete their approach before the procedure would need to be discontinued for safety reasons.

With the availability of a reliable active wake prediction and detection system, dynamic wake vortex separations between each pair of aircraft approaching a single runway will be possible. Under different forecast wind conditions, the wake prediction system would provide different minimum safe wake vortex spacings for each trailing aircraft on final approach, based on the weight class of the leading aircraft. The concept is applicable in IMC weather conditions down to Category I minima or better. Such a concept for dynamic reduction of separations on a single arrival stream was demonstrated in AVOSS.

Dynamic changes in predicted safe separations would require decision support tools for controllers so that the projected separation adjustments are used effectively and so that these changes are largely transparent to controllers. Spacing tools will certainly be required for the final controller. Tools may also be required for a traffic manager position, if one exists, and for the feeder controllers so that traffic being delivered to the final controller reflects appropriate responses to the changes in separation values.

For the latter function, the active wake detection and prediction system could provide approach control with the current dynamic separation standards in effect for each pair of aircraft types for the appropriate look ahead time and an estimated AAR based on the traffic mix of the expected arrivals during the future time period and these dynamic separation standards. This may help the traffic manager and feeder controllers plan the traffic feed to the final controllers. It may also help final controllers with establishing the desired sequence on final approach with the knowledge of the current minimum separation factors for each pair of weight classes. Additional decision support tools may be needed for properly accomplishing these functions.

To implement dynamic separations for each trailing aircraft on final approach, a controller tool such as the ghosting tool described in Section A.2.1 would need to be implemented. WakeVAS would provide the separation values for each trailing aircraft based on the wake behavior predicted for its lead aircraft. These separation values could then be used by the ghosting tool to present a ghost target on final at the target spacing for each aircraft. In addition to capacity gains enabled through reduced in-trail separation, the more accurate spacing of aircraft using the ATC tool may provide additional gains through a reduction in the variability of spacing actually achieved on final approach.

This ghosting tool would have a similar CHI to the current CRDA; however it will also have an interface to the active wake prediction and detection system in order to generate target ghosts at the required separation values. Figure A-7 shows a depiction of such a ghosting tool.

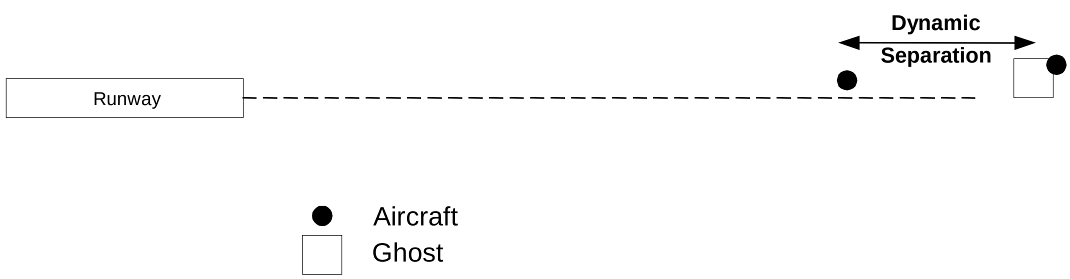

Figure A-7. Depiction of Ghosting Tool for Dynamic Spacing on Single Runway Approaches

The active wake prediction subsystem would need to provide a highly reliable forecast of maximum wake persistence in the approach path for each pair of equipment weight classes. This forecast would need to be available 10-15 minutes prior to landing so that each flight could be established on its approach with the appropriate dynamic spacing, representing the minimum safe separation from the preceding aircraft during the period of the approach. The dynamic separation standard should not normally be adjusted while the flight is on the approach. Consideration of differences in the minimum spacing for wake vortex avoidance required on the downwind, turn and final approach legs would also have to be included in the controller ghosting tool used to implement the procedure. Finally, provision would have to be made for specifying the sequence in a simple manner so that the target ghost can be generated appropriately. This may imply additional workload for controllers, and it would have to be determined through simulations whether the additional workload is acceptable. The CHI in STARS may make this easier to accomplish.

The active wake detection subsystem is essential to provide real-time feedback of each aircraft's observed wake to the prediction subsystem. This would provide real-time quality control measurement on the current separation standard, and facilitate the required safety net. This information would be used to update the current dynamic separation standard as required, and would have to be reflected in the target ghosting positions if it reflects an increase in the safe spacing value. Reductions in minimum safe spacing would not be indicated to targets already being provided ghost targets, for stability.[21] Indications (i.e., alerting) that a change has occurred would also have to be provided to the approach controller, if they increase the required separation for targets already being spaced on final. Such changes will not normally be desirable and the design must minimize them. In extreme cases, such a sudden increase in separation standard may require vectoring of flights on the approach or even a go-around of the next flight to land, but the system should be designed so that such extreme measures are very unlikely.

The second enhancement in Track A-3 incorporates the downlink of aircraft approach configuration and weight (in addition to the final approach speed downlinked in Track A-2). Since wake vortex intensity increases with aircraft weight and is also affected by aircraft configuration (e.g., flap settings), the knowledge of these variables will enable WakeVAS to make more accurate predictions of wake behavior. An additional benefit to this enhancement is the ability to establish safe in-trail separations based on individual aircraft type or perhaps clusters of types, rather than the current weight class. When establishing the current standards using weight class, it is reasonable to assume that the worst-case wake behavior for any aircraft in a weight class was used in establishing safe in-trail separation requirements. Within a particular weight class, the initial intensities of wakes generated by different type aircraft can be very substantial (a factor of two or more, as shown in the aircraft characteristics table in Appendix C). Establishing in-trail separation requirements by aircraft type can result in a significant reduction due to avoiding the need to base the requirement on a worst-case aircraft type.

A third enhancement in this track may be to utilize cockpit-based tools to provide pilots with the desired separation values and allow pilots to achieve the desired spacings more accurately and with fewer controller-pilot communications with a cockpit based approach spacing tool.

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21 Since the spacing already being provided would exceed the new minimum.

A.2.4 Track A-4: Visual-like Separations in IMC with Advanced Technology

The base procedure for this track is the wake avoidance procedure for pilots described in the AIM. The procedure relies on the pilot's visual observation of the aircraft generating the wake and the pilot's estimate of where that wake would exist behind the generating aircraft. This estimate is based on the wake sinking below the generator's flight path (if out of ground effect) and transporting laterally with the wind.

As described earlier in Track C-4, the enhancement for visual-like operations with WakeVAS may be to place cues on a CDTI on the flight deck that would indicate own ship position with respect to the leading aircraft such as to aid in vertical positioning to stay above the glide path of the traffic for wake avoidance. Again, in conjunction with C-EFR, this may provide some capacity gains in visual conditions.

Also in the far-term, synthetic vision technology could provide a three-dimensional visualization to pilots showing wakes from other aircraft (as well as positions of other aircraft) with the intent to certify this tool for use in visual-like operations.

A.3 WakeVAS Technology Applications for Departures (Single, CSPR), Intersecting Runways and Mixed Arrival/Departure

This set of applications explores possible procedures for operations involving departures from single runways, CSPR, and intersecting runways. Situations where runways are dedicated to departures as well as mixed arrival/departure operations are considered. Figure A-8 shows an overview of departure evolution options considered, starting with base procedures on the left and progressing in time toward the right.

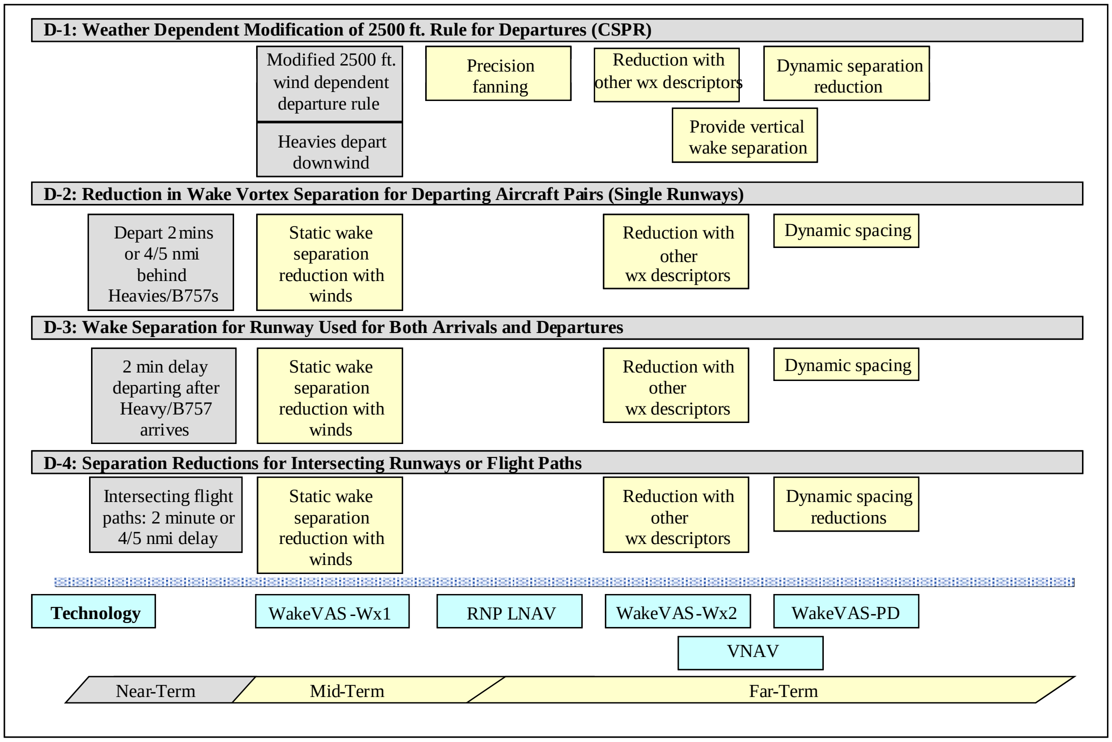

Figure A-8. Departure, Intersecting, and Arrival/Departure Evolution Options

All procedures in this section apply to all meteorological conditions, VMC as well as IMC.

A.3.1 Track D-1: Weather Dependent Modification of 2500 feet Rule for Departures

The base procedure for Track D-1 is the FAA proposed mid-term procedure for wind-dependent CSPR spacing for departures (Figure A-9). For certain crosswind conditions, wakes from departures off a downwind runway transport with the wind and would not reach the upwind departure runway. Departures from the upwind runway do not require wake separation from a previous departure off the downwind runway for this procedure. In-trail separation requirements between aircraft departing from the same runway are not affected. An additional operational benefit to this procedure is that no departure delay would be incurred by an intersection departure from the upwind runway. Currently, a three minute delay is required for intersection departures for some aircraft pairs. If operationally feasible at a particular airport, additional capacity can be gained by restricting departing Heavy aircraft to the downwind runway.

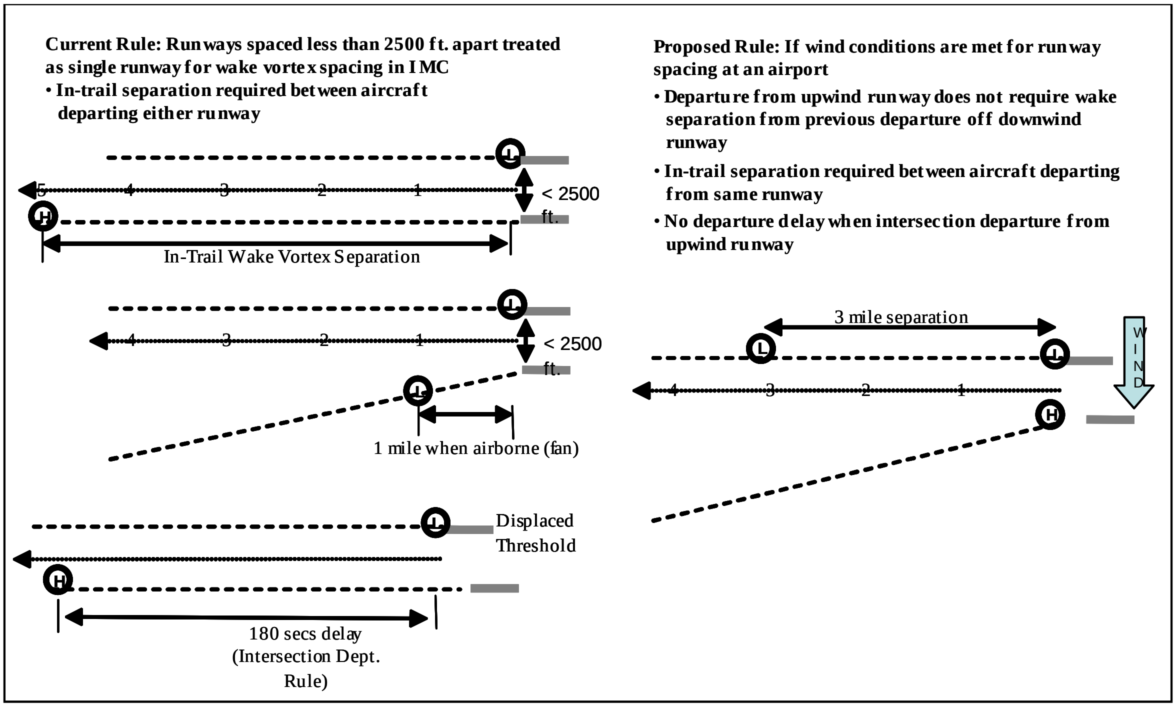

Figure A-9. FAA Proposed Mid-term Departure Procedure

The first enhancement in Track D-1 is the use of RNP LNAV to accomplish precision fanning of departures. Some airports can currently fan departures (assign them headings that diverge by at least 15 degrees within one mile of the runway) and thereby reduce initial IMC separation for successive departures from CSPR to 1 nmi. Airspace congestion and noise abatement procedures can limit where and when fanning can be used. If course guidance (e.g., with RNP based navigation) is provided for fanning, rather than just assigned headings, the departure tracks could be more accurate and possibly result in additional situations where fanning could be used to increase departure rates.

The second enhancement builds on the FAA mid-term proposal by adding the consideration of the effect of turbulence and other weather factors on the intensity and movement of wakes. WakeVAS turbulence and weather information could be used to determine cases when wakes will decay and not be a factor for aircraft departing the parallel runway. The knowledge of EDR and other weather factors and their effect on the time for a wake to decay to background turbulence level, combined with the knowledge of wake transport behavior, may provide additional opportunities to safely lower runway spacing requirements.

A third enhancement would be to use VNAV to provide guaranteed vertical separation between departures. This procedure would involve assigning a trailing aircraft a steeper climb gradient than that being followed by the leader aircraft. The climb gradient of both aircraft would need to be operationally acceptable and both aircraft would need to be following vertical guidance to ensure that vertical separation is maintained. Use of this procedure when a Heavy aircraft is the leader and will have a relatively slow rate of climb could eliminate a three minute departure delay for the trailing aircraft departing from a displaced threshold if the trailing aircraft meets these two conditions: 1) it is airborne well before the point when the Heavy aircraft begins generating wake turbulence and 2) it accepts a steeper climb gradient to guarantee remaining above the Heavy wake.

Standards would need to be determined to which aircraft VNAV conformance can be assured, and design of paths to provide adequate wake separation would need to be designed. It would be expected that only certain Large aircraft would be capable of reliably achieving a path with a takeoff point substantially before the leading Heavy or B757, and an angle of climb that exceeded the angle of climb of the leading Heavy/B757, so that the two paths maintain the required vertical separation. The vertical navigation segment would need to extend until another form of separation could be applied. An indication of which aircraft could execute the required VNAV procedure would have to be provided to the tower controller prior to establishing the line-up sequence for that runway. In-trail distance separation requirements could also be reduced for cases where the trailer is guaranteed to remain above the Heavy wake for even threshold departures. Scenarios such as the trailing aircraft losing partial power during takeoff and not being able to maintain a steeper climb gradient than the Heavy aircraft would need to be analyzed to evaluate safety considerations.

The fourth enhancement in Track D-1 would use WakeVAS predicted wake decay and transport information to determine dynamic spacing intervals between each pair of departures. WakeVAS would include sensors to measure wind, turbulence, and other weather factors and would use validated algorithms to predict the wake behavior of each departure based on parameters for the aircraft type (e.g., wing span, maximum takeoff weight, minimum takeoff speed, takeoff configuration). WakeVAS would also use active detection of wake position and intensity to continually monitor the performance of the wake prediction system. One option for the use of WakeVAS for reducing separation requirements for departures is to define departure corridors for each aircraft and predict when the wake of the leading departure would be clear of the path for the trailing departure. Departure paths can vary substantially from one aircraft to the next depending on aircraft performance, departure fix assignments, and whether departures are being fanned. Building knowledge of these factors into WakeVAS for each aircraft could be a substantial effort and still may result in large departure corridors to enclose the uncertainty in aircraft departure path. Use of RNP LNAV and VNAV would complement this type of approach by limiting the dimensions of the departure corridors due to the increased certainty in vertical and lateral paths. Another option would be to only use wake decay times to set inter-departure separations, predicting when the wake of the previous departure will decay to background turbulence level.

A.3.2 Track D-2: Reduction in Wake Vortex Separation for Departing Aircraft Pairs (Single Runways)

The base procedure for this track is the current departure rule calling for 2 minutes or 4 or 5 nmi behind B757s or Heavy aircraft.

The first enhancement could use WakeVAS wind information in the mid-term timeframe to determine when wakes will be transported clear of the next aircraft's departure path. Data will be collected over an extended time period documenting when each wind condition reliably transports the wake of certain class aircraft such that the wake is no factor for the next departure. This historical data can then be used to establish a departure procedure that can reduce or eliminate wake separations when appropriate. As discussed in Track D-1, the paths of departing aircraft are variable and the area that must be guaranteed to be wake-free is larger than the corresponding area for arrivals. Because of this, the wind dependent enhancement for single runways may be limited to providing guidance regarding which way to launch the next aircraft to be free of wake turbulence limitations.

The second enhancement takes advantage of WakeVAS turbulence and other weather information in the mid to far-term to determine cases when wakes will decay and not be a factor for the next departure. The knowledge of EDR and other weather factors and their effect on the time for a wake to decay to background turbulence level, combined with the knowledge of wake transport behavior (from the first enhancement) may provide opportunities to safely lower in-trail wake separation during certain wind and turbulence conditions.

In the far-term, WakeVAS active wake prediction and detection may enable the third enhancement to allow dynamic wake separation values to be determined for each departure. Departures may go out on a common track or may be fanned after takeoff. The system will need to consider the common path segments to predict potential reductions. It will be easier to reliably predict the reduced spacing necessary if the trailing aircraft is fanned to an initial heading different from the preceding flight immediately after takeoff. This is because the airspace volume over which the wind and wake behavior must be predicted is in this case much smaller than the volume encompassing entire departure path of a flight. Given predictions of wind direction during the first minute or two of flight, it will be desirable to fan departures so that flights are given initial headings upwind of a preceding Heavy or B757 aircraft. This will reduce the airspace volume of any wake encounter to the minimum. With the headings given during fanning, the divergence rate is fairly large. For example, if a trailing aircraft is traveling at an average speed of 150 knots with a 15 degree divergence from the preceding path, then the flight will be separated by 2500 feet from the preceding aircraft's path in 38 seconds.

Separation reductions may to standard radar separation or to intermediate values. Controllers anticipate separation in launching departures. Consideration will have to be given to these practices in designing the required operational concept and the interface of the required controller decision aid. For the safety of each departure, wakes (decay and/or transport) must be predicted very reliably during the period each departure is in the immediate path of its predecessor. This period is less than one minute when fanning to alternate headings is used, and several minutes otherwise. It must be recognized that if the predictions are declared incorrect, they must be so declared before the succeeding aircraft is launched. Once an aircraft has started its take off roll and reached a certain speed, it will not be possible for it to abort its take off. In addition, to give the ground controller useful information to plan the departure sequence for each departure runway (staging) in order to optimize the available departure capacity, it would be desirable for the wake prediction to be reliable out to 15 to 20 minutes in the future. Further studies with controllers at specific airports are required to determine these prediction reliability criteria.

A.3.3 Track D-3: Wake Separation for Runways Used for Both Arrivals and Departures

Under current rules for runways used for both arrivals and departures, the soonest a departing aircraft can begin its takeoff roll is either after the previous arrival clears the runway or two minutes after a B757 or Heavy aircraft lands.

The first enhancement takes advantage of WakeVAS wind information to identify periods when the wind will transport the wake of an arrival away from the departure path of the next aircraft departing the same runway. Based on data collected over all relevant conditions, a maximum observed wake vortex residence time for wakes of significant strength would be established for wakes generated by aircraft in each weight class and for each crosswind value. WakeVAS wind data would then be used to determine current and near-term crosswind forecast. Based on the forecast crosswind value, a maximum wake residence time and corresponding departure delay will be determined. The minimum safe departure delay will be provided to ATC through an interface. The region of concern for this procedure is much smaller than for other departure procedures since the wake of the arriving aircraft will only be a factor between the point the departure becomes airborne and the point at which the arriving aircraft's nose wheel touches down and its wake generating potential is greatly reduced. The fact that this entire area is within the airport boundaries, near ground level, and only several thousand feet in length should result in a very high reliability crosswind measurement and forecast capability.

The second enhancement would use WakeVAS turbulence and other weather information to determine cases when the wakes will decay (even before transporting clear of the region of concern) and not be a factor to the next departing aircraft. This capability is based on the relationship between EDR and wake decay determined from the data collection effort described in the first enhancement.

In the far-term, WakeVAS active wake prediction and detection may enable a third enhancement to allow dynamic departure delay values to be determined based on current and forecast wind and weather conditions as well as information on aircraft specific parameters such as wing span, maximum landing weight, and minimum landing speed. Data down-linked from aircraft or provided by Airline Operation Centers (AOC) providing actual weights and target landing speeds for specific arriving aircraft would enable even more accurate predictions of wake transport and decay.

A.3.4 Track D-4: Separation Reductions for Intersecting Runways or Flight Paths

Wake vortices encounters are most dangerous when aircraft are in-trail (i.e., in an axial encounter) from one another since the following aircraft can be subjected to large rolling moments for potentially several seconds. An encounter with a wake perpendicular, or nearly so, to the orientation of the wake tube along an intersecting flight path (a transverse encounter) results in a succession of offsetting pitch variations that are isolated to a brief period of time. However, separation standards for transverse geometries are the same as for axial geometries. We could reasonably expect by this reasoning that the wake spacing between aircraft on intersecting flight paths could be reduced to provide the same degree of protection as the larger separations for axial geometries particularly since the aircraft on these flight paths could be at much different altitudes so that a wake encounter would be all but impossible.[22]

The procedure and enhancements in this section apply to separating an aircraft using one runway from another aircraft using an intersecting runway or a nonintersecting runway when the flight paths of the two aircraft intersect. The following tables summarize the base procedure for this track, which is the current wake turbulence separation and arrival/departure separation for the cases of an arrival followed by an arrival, an arrival followed by a departure, a departure followed by an arrival, and a departure followed by a departure. The wake turbulence separation shown in Table A-4 applies only when the first aircraft through the intersection is a Heavy or a B757. When wake vortices are not a factor, Table A-5 shows the dependence of a flight on the status of the previous flight through an intersection. This dependence indicates the limit to which the separations could be reduced, and must be considered for the development of any new procedure or standard.

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[22] Though there could be stresses applied to the airframe that are undesirable if encounters were common.

Table A-4. Wake Turbulence Separations for Intersecting Runways or Parallel Runways When Flight Paths Intersect

	Followed by Any Class Arrival	Followed by Any Class Departure
Heavy/B757 Arrival	Standard WV separation (4-5 nmi) for IFR Wake Advisory when trailing aircraft is VFR (3-10-4d.2)	Two minutes (3-9-8d) (not specified as to when this is applied, but presumably it is: issue take off clearance 2 min after leading Heavy or B757 passes intersection) (non-waivable) (3-9-8e) All times (IFR or VFR)
Heavy/B757 Departure	Two minutes or the appropriate radar separation minima (4-5 nmi) (3-10-4c) Probably at all times (IFR or VFR)	Two minutes (3-9-8c) (Issue take off clearance 2 min after leading Heavy or B757 starts take off roll) (non-waivable) (3-9-8e) All times (IFR or VFR)

Table A-5. Dependence Between Flights For Intersecting Runways When Wake Vortex Is Not a Factor

	Followed by Arrival	Followed by Departure
Arrival	Arrival does not cross landing threshold or flight path until preceding aircraft is: • Clear of runway, • Holding short of intersection, or • Past the intersection	Departure does not begin takeoff roll until preceding aircraft is: • Clear of runway, • Holding short of intersection, • Past the intersection, or • Crossed the runway
Departure	Arrival does not cross landing threshold or flight path until preceding aircraft is: • Past the intersection or • Airborne and turning to avert any conflict	Departure does not begin takeoff roll until preceding aircraft is: • Past the intersection, • Crossed the runway, or • Airborne and turning to avert any conflict

The first enhancement for this track uses WakeVAS wind information to determine when the wind will remove the wake from the area of concern for the next aircraft. The wake movement as a function of the weight class of the generator and the wind direction and strength is derived from analysis of wake data measured under highly instrumented conditions with all relevant weather data and aircraft type data collected for many thousands of arriving and departing aircraft. The area of concern for intersecting runway operations is very small compared to the area related to arrival and departure paths for single runway and CSPR operations. The area is usually within the perimeter of the airport, making installation of sensors much easier than if these sensors had to be installed off-airport. For intersecting runway operations, there can be many combinations of ATC rules that need to be applied based on the types of aircraft involved and whether they are departing or arriving. Separate rules for in-trail separation between aircraft on each of the arrival or departure streams must also be met for each aircraft. The inter-play among these many ATC rules needs to be analyzed further to determine which rules are the most constraining for each situation. Then the opportunities for safely relaxing wake separations based on wakes being safely removed from the region of concern by the wind can be explored further and the capacity improvements and likely benefits estimated.

The second enhancement takes into consideration opportunities when WakeVAS information on turbulence and other weather descriptors would enable the accurate prediction of decay time and determine cases when the wake would decay to background turbulence levels prior to transporting out of the area of concern, thereby reducing the delay due to wake vortex separation that is necessary for the next arrival or departure aircraft. Again, this delay reduction is predicated on the wake vortex separation rules for intersecting runways or flight paths being the constraining requirement.

The third enhancement uses WakeVAS active wake prediction and detection to predict (and monitor the quality of each wake prediction) the movement and decay of wakes more accurately and enable further reductions when the wake will be known to be clear of the area of concern.

This enhancement proposes the reduction of one or all of the spacings in Table A-4 for aircraft on intersecting paths.[23] The reduced standard would be based on extensive wake measurements collected over a wide range of environmental conditions. The lower limit that the separation could potentially be reduced to for arrivals following departures would be the separations in Table A-5. Consideration would be given to conditional changes in separation standards that are based on one or more of the following:

- The specific facility
- Certain aircraft types or combinations of aircraft types
- The geometry of the flight paths such as the angle of intersection of the flight paths and the altitude difference of the aircraft at the point of intersection

[23] The separation of departure behind departure is highly geometry dependent, and may not be a candidate for reductions.

This application includes three potential separation standard reductions which would dynamically reduce the current 2 minute or 4/5 nmi wake vortex separation under specific conditions based on real-time measurements of wakes at the intersection:

1. Dynamically reduce the wake vortex separation required for situations where the paths of two airborne aircraft will intersect. This dynamic reduction is based on a reliable prediction of the wake transport or decay behavior for a certain range of environmental conditions in the airspace through which the paths of two airborne aircraft would intersect.
2. Reduce the wake vortex separation required for aircraft with certain takeoff and climb performance which depart after a Heavy or B757 arrives on an intersecting runway. This separation reduction is based on a reliable prediction that, given the predicted environmental conditions, departing aircraft of certain aircraft types would remain on their takeoff roll until passing under the wake of the arriving aircraft and takeoff safely beyond its wake.
3. Reduce the wake vortex separation required for aircraft which arrive after a Heavy or B757 departs on an intersecting runway. This separation reduction is based on a reliable prediction that arriving aircraft would not pass through the airspace in which the wake of a previous Heavy or B757 departure would be expected, given the predicted environmental conditions.

The first application will require the active monitoring and prediction of aircraft wake vortices in the airspace volume containing all of the intersecting paths, allowing for their transport or decay from the time they are generated until the time at which the following flight would pass through this volume. It must be established whether wake decay or wake transport behavior can be used to establish a reliable dynamic separation standard for intersecting flight paths. It is conceivable that wake decay may be the dominant factor for some of these procedures. The airspace volume of interest is also bounded by the uncertainty of the aircraft trajectories and the wake motion, but should be relatively small since the aircraft are near liftoff or touchdown. By comparison, in-trail or parallel runway procedures that require real-time wake sensing have relatively large areas along approach paths where wake vortices need to be avoided. In many cases, the intersection point of the runways or flight paths will be within a few hundred feet AGL. The close proximity of the area of concern to the airport or the surrounding area, and its smaller extent should allow the deployment of sensors (such as LIDAR) to provide accurate current information regarding the movement and/or decay of wake vortices.

It is conceivable that the observed behavior of the vortices over the limited area of concern, together with a weather prognosis may enable reliable extrapolation to small amounts of time in future. This could then become the basis for dynamic standards based on actually observed wake behavior. Of course, any such concept would need to be designed so that it is operationally useable by controllers.

The second application provides an opportunity to improve the departure capacity for airports with intersecting runways similar to those shown in Figure A-10. In this configuration, arriving aircraft will cross the departure runway at a point where certain types of departing aircraft will still be on their takeoff roll. To safely use this application, it would have to be demonstrated that wakes of arriving aircraft on an intersecting path do not pose a threat to departing aircraft while on their takeoff roll. It would also have to be determined that the wake of the arriving aircraft would not transport to a point at or beyond the departing aircraft's liftoff point. Under these environmental circumstances, and with appropriate wind and wake vortex measurement and prediction systems, procedures could be developed to guarantee that a departing aircraft will not be airborne until after it passes under and/or past the wake vortices of the preceding arrival on the intersecting path. In this case, the 2 minute departure delay for wake turbulence would not be necessary.

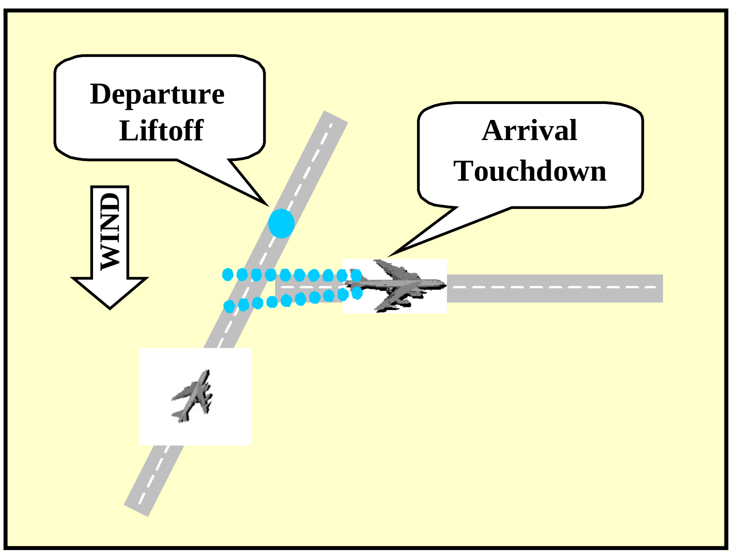

Figure A-10. Departure Lifts Off Past Arrival's Wake

A third application where the accurate prediction of wake vortex transport and decay can result in capacity improvement is where a Heavy or B757 departure shuts down arrivals on an intersecting runway for 2 minutes (or appropriate radar separation minima). Figure A-11 illustrates this situation. Some airports with this configuration[24] currently discontinue arrivals on the rightmost intersecting runway for 2 minutes after a Heavy jet departure. With reliable prediction and detection of wake vortex transport and decay, a procedure could be developed to allow arrivals to be spaced closer than the current standard after an intersecting

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24 For example, Chicago O'Hare 32L departures, 9L arrivals

Heavy jet departure during environmental conditions where the wake could be guaranteed not to intersect with the arrival's flight path. Thus, the arrival path will not pass through the airspace in which the preceding departure's wake is expected to be.

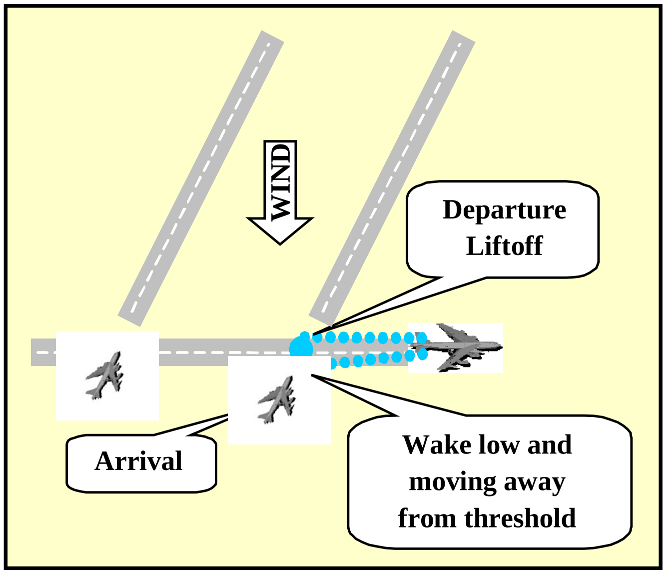

Figure A-11. Departing Heavy Jet with Intersection Arrivals

The implementation of these three applications will require that the responsible controller be provided with enough information about the arrival and departure flight paths to determine whether they will intersect or not and what the minimum required spacing for wake turbulence avoidance is.

A controller decision aid would be developed that would calculate the bounds on arrival and departure flight paths based on aircraft type and environmental conditions, monitor and predict wake vortex movement, and indicate to the controller the spacing necessary to avoid any encounter with the preceding aircraft's wake vortices. In order for the decision aid to properly calculate the arrival and departure flight paths, the following information would need to be available:

- Runway configuration and intersection distance from both runway thresholds
- Aircraft type and takeoff and climb performance to determine the bounds on the airspace volume through which departure aircraft will pass at the intersection
- Bounds on the airspace volume through which arrival aircraft will pass at the intersection

- Possibly the maximum height wake vortices could rise under the current environmental conditions
- Monitoring and prediction of environmental conditions at the intersection
- Active monitoring and prediction of wakes near the intersection

Additional issues that need to be investigated are:

- Development of reliable wake monitoring and prediction system in the area of runway intersections is needed
- Verification may be needed of the maximum height to which wake vortices can rise above the point of generation for specific weather conditions
- Development of a controller decision aid indicating when intersecting arrivals and departures can be permitted without wake turbulence considerations. Lead times for indications will depend on the procedure being used, and may also depend on the airport. Short lead times may be adequate for certain airports[25]. For some airports, larger lead times may be needed for effective departure staging.[26] In some cases, indication may be needed with 10-20 minutes of lead time before intersecting operations need to be discontinued to allow time for arrival flows to be adjusted without significant disruption to arrival operations
- Short-term weather forecasts over the 10-20 minute time period mentioned above will need to be developed
- Complexity and program dependencies of interfacing a decision aid with existing tower automation
- Reliability of aircraft performance values. May be mitigated by VNAV clearances. Aircraft capable of accepting the relevant VNAV clearances would have appropriate designations for controllers to be able to clear them accordingly

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[25] For example LGA has indicated that 5-10 minutes lead times would be adequate for creating the gaps needed.

[26] Chicago O'Hare may need up to 20 minute lead times for staging their departures appropriately when reduced separations can be used.

A.4 Safety Related and Other WakeVAS Technology Applications

A.4.1 Track S-1: Wake-related Advisories for Visual Operations

When visual separation is provided by pilots, wake vortex avoidance is a pilot responsibility. Pilots are provided guidance in AIM regarding safety with respect to wake vortices. Pilots learn to visualize the location and movement of wakes from the traffic of concern so that the risk of wake encounter is minimized. It is a stated policy of the International Federation of Airline Pilots Associations (IFALPA) that wake vortex visualization capabilities be developed [6]. The ALPA endorses this policy. This procedure aims at improving pilot's situation awareness of wake related information, including cockpit visualization capabilities.

The first enhancement to the base procedure would be to use WakeVAS wind information to prepare wind advisories, notifying pilots when conditions make it likely for wakes from parallel approach courses to transport to their approach course. This capability would be in the mid-term timeframe.

This is an advisory procedure, which is of primary value during visual approaches when each pilot accepts responsibility to space their aircraft from the preceding aircraft on the same approach path. (Accepting visual separation responsibility includes providing own wake turbulence separation.) No changes in separation standards are implied in this procedure. FAA guidance to pilots describes the winds along the approach path. Pilots are taught about the relationship of winds to wakes, and are generally believed to consider the effect of winds in their approach planning in visual conditions in order to enhance their awareness of and thus mitigate the likelihood of encountering the potential wake hazard. However, wind information is currently only readily available for the surface. Winds at altitude are frequently quite different from winds on the surface. Providing better wind information along the approach should enhance the pilot's awareness of the environment, thus improving the safety of the approach.

This procedure will broadcast ITWS wind information for the terminal area to pilots. This procedure would be useful to all flights, whether they are approaching a single runway, one of two closely spaced runways or one of two runways with intersecting paths. Departing flights, if the prediction is tailored to the appropriate departure path, could also use the procedure.

For additional information on the procedure and associated issues, see [27].

Once active detection of wakes is available from WakeVAS in the far-term, the wind advisory service could be upgraded to provide wake advisories based on individual aircraft wakes and aircraft positions on the final approach path. Both of these enhancements are intended to improve safety through pilot situational awareness.

This application extends the wind advisory capability to its logical extension based on knowledge of wake vortex behavior. Expected transportation or demise of wakes could be computed based on one or more of several criteria, for example:

- Transport of wakes from crosswinds or sinking of the wakes
- Simple wind criteria such as a derivative of the wind ellipse[27]
- Decay computations based on turbulence measurements and various aircraft types and nominal weights and airspeeds

This advisory information will have the legal status as weather information. It will not be legally binding and will not be used for computing separation standards or values. Its use will be strictly advisory and its dissemination will be based on providing the best possible information as advisory information to pilots to enhance the safety of flight. The intent of this procedure is to reduce the workload on the pilots by translating the weather information to wake turbulence advisories using the best available understanding of wake turbulence behavior.

It is envisioned that this application will evolve over time. Initially it may involve only computing wake transport with winds on long final, reflecting a widely accepted model of wake transport out of ground effect. As more knowledge of wake behavior is attained by the research community, other characterizations such as decay or bounce may be included.

Parameters will be developed for generating advisory information such that pilots can easily understand its implications in conducting normal approaches under visual conditions. Multiple data would be communicated through the use of these advisories, for example:

- Expect Runway 18 approach to be clear of wake turbulence when at least 2 miles behind leading traffic
- Expect Heavy or B757 wake to persist less than 3 nmi
- Expect Heavy or B757 wake to rise not more than 200 feet at altitudes under 3,000 feet

Wake persistence along the approach path would likely need to be converted to a mileage, as pilots and controllers both can use mileage information much more easily than

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[27] In the data collected in the 70's, wakes near the runway were found not to be resident for more than 80 seconds within a single stream approach corridor when winds are stronger than 5.5 knots cross wind or 12.5 knots headwinds [28]. Of course, many modern aircraft were not represented in that data set. Additional data would also have to be collected on long final. However, with such additional data, it may be possible to develop a derivative of the wind ellipse model to help provide simple wake hazard advisories.

time information without the addition of other aids. Information could perhaps also be provided on the maximum expected wake rise above the approach path to give the trailing pilot information to help the execution of a higher and longer to touchdown approach behind a leading flight to the same runway. Wake persistence in approach path must also consider the “cone” of possible approach paths that occur under visual conditions due to variation in pilot navigation. If a wake is being transported out of the path of a trailing flight by crosswinds, if the trailer is slightly downwind of the leader, larger spacing from the leader is required than if the trailer exactly followed the approach path of the leader or was upwind from it. Since the existing methods of communicating the products to the cockpit (ATIS, ACARS, TWIP) do not easily allow a customized message for each aircraft pair, the messages sent will need to be conservative.

Advisories would be coded to fit within the limitations (i.e., number of characters) of the distribution method used. This information would be automatically generated and available via ATIS, cockpit printers, or other means to be determined. If an advisory is broadcast to all flights, then it would have to include all weight classes. If it is specifically transmitted to each flight at top of descent, then it could be made specific to the leader’s equipment type.

The wake vortex visualization capability described here does not require on-board wake vortex sensors. The feasibility of on-board wake sensors has not been demonstrated. Their cost effectiveness is subject to even more question. The wake vortex visualization capability implied here is based either on ground based information from WakeVAS up-linked to aircraft or visualizations developed through other means.

It is proposed that the cockpit wake vortex visualization capability be developed in an evolutionary manner. It should be simple and intuitive; it should reflect the internal model pilots utilize in visualizing wakes of preceding or other relevant aircraft. In all cases, such visualization should be at pilot’s discretion, i.e., the pilot should be able to turn the wake visualization capability on or off.

A CDTI may provide an appropriate platform for wake visualization.[28] An ADS-B data link may provide capabilities that may significantly enhance the type of information that a wake vortex visualization capability could provide. However, other modes of wake vortex visualization may be possible and should be explored.

Several steps are described for enhancing pilot situational awareness and allowing more accurate estimation of the location of hazardous wakes. The first step is a visualization tool for replaying recorded ATC radar tracks together with recorded wake sensor data to help pilots visualize current traffic and current separations from wakes. This capability could

[28] As defined by RTCA [33] the CDTI does not have to be a visual display; it includes other modes of traffic display.

serve as a training tool for pilots to help them learn to estimate wake transport and decay more accurately. It could also serve as a platform for use in exploring future wake vortex procedures and enable visualization of the wake separations that would result.

The other steps are described in Section A.1.4.

A.4.2 Track S-2: Wake Avoidance at Glideslope Intercept

One region where pilots have informally reported encountering wakes is in the vicinity of glideslope intercept while executing an approach. The authors are not aware of any extensive data collection efforts in this region (from 4 to 11 nmi out on final). Further documentation of the conditions surrounding these wake encounters would help researchers to understand the potential causes and would suggest ways to modify current operations to reduce their occurrence. WakeVAS algorithms could be used to predict the location and strength of wakes from aircraft in simulated scenarios and analysis tools could detect when trailing or crossing aircraft might encounter wakes of significant intensity. Once the cause of these wake encounters is better understood, WakeVAS could be used for prediction and detection (if sensors can be added to monitor this region) of wake transport and decay and could determine safe wake spacing requirements at glideslope intercept points based on aircraft types and altitudes. AILS could also be modified to present the pilot with information on wake location (up-linked from WakeVAS) during approach providing the pilot greater situational awareness.

A.4.3 Track O-1: Aircraft Wake Vortex Categorization

Aircraft are currently categorized with respect to their wake vortex characteristics based simply on their gross take off weight. Although aircraft wake generation certainly depends on aircraft weight, there are other significant factors such as wing span and airspeed of the leader and follower and roll susceptibility of the follower that also directly affect both wake generation, susceptibility and controllability with respect to wakes. Research indicates that the current categorization can not be considered to provide a uniform level of safety with respect to wake encounter [22]. Considerable room appears to exist in refining the method of classification of aircraft into wake-related categories so that a more rational and more uniform safety basis may be provided. In particular, no basis exists today of anticipating the wake separations implications of new aircraft. The design of the new class of super-jets would benefit from the prospect of a rational basis for defining separation standards for the new aircraft.

Finally, such re-classification of aircraft will also necessarily have specific implications in terms of system capacity. It may be possible to refine wake classification so that system efficiency is also improved. In the current categorization, the same spacings are applied to every aircraft in a category, despite the fact that there can be a substantial difference in weight between the lightest in a category and the heaviest. An increase in the number of categories would improve this issue, but at a certain point this would become unmanageable for controllers. The current boundaries between categories are arbitrarily defined and would be so for any other categorization metric. There are several different choices for the category boundaries that have similar or equivalent levels of risk associated with them. It may be possible to choose these boundaries to optimize capacity without sacrificing safety. WakeVAS algorithms used for prediction and detection of wake transport and decay could be applied to the wake generation aspect of the reclassification. Section 4 contains some discussion of how a reclassification of aircraft into eight clusters would work with the boundaries between clusters based on the initial wake intensity predicted by WakeVAS at an aircrafts maximum landing weight and minimum landing speed (worst case). Section 6 describes a concept of use that utilizes wake clusters for determining wake separations but provides information to controllers in a manner consistent with their current use of weight classes, eliminating the need for controllers to learn twice as many aircraft categories as current, but retaining the benefit of basing wake separations on the cluster each aircraft is categorized in.

A.4.4 Track O-4: Heavy/B757 Passing Procedure

Currently, controllers are responsible to determine that during visual approaches to closely spaced parallel runways, a Heavy or B757 aircraft will not pass another aircraft, and a Large will not pass a Small aircraft. This restriction is to protect the smaller aircraft from the wake of the larger aircraft after it is passed. Ensuring that aircraft passing will not occur increases the workload of the final approach controller. This procedure will establish conditions when this rule can be suspended when the Heavy or Large is on a particular runway, or perhaps set some limits to how much the Heavy aircraft could pass. (e.g., pass the leading aircraft by no more than 1 nmi), based on a reliable current prediction of winds along the approach path. The procedure will determine wind values, and perhaps overtake distances, as a function of runway separations. It is possible that this procedure may also provide a small increase in arrival capacity, since it allows the following aircraft to pass, hence allowing the aircraft following in trail behind the passing aircraft to follow closer as well, without changing the current in-trail separation standards. This procedure could also be incorporated as part of a wake advisory to the two aircraft.

It is hoped that the procedure could be based on wind profile only. However, if this is not possible, then the procedure will require both an active wake transport prediction and detection system.

Appendix B

Departure Separation Rules for Single Runways and Closely Spaced Parallel Runways

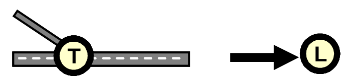
The material in this appendix summarizes the current departure rules found in the Controllers' Handbook (FAA Order 7110.65)

Single Runway: *Visual Departures*

Same Threshold Departure

Trailing Aircraft Lead Aircraft

Intersection Departure



Same Threshold Departure

Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	6000&AB	6000&AB	6000&AB	6000&AB
Large	6000&AB	6000&AB	6000&AB	6000&AB
B757	2min or 5nmi	2min or 4nmi	2min or 4nmi	2min or 4nmi
Heavy	2min or 5nmi	2min or 5nmi	2min or 5nmi	2min or 4nmi

Intersection Departure

Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	6000&AB	6000&AB	6000&AB	6000&AB
Large	3min	6000&AB	6000&AB	6000&AB
B757	3min	3min	3min	3min
Heavy	3min	3min	3min	3min

Rule Code	7110.65 Paragraph	Description
6000&AB	3-9-6a	Trailing aircraft does not begin its takeoff roll until lead aircraft is 6000 ft away and airborne
2min	3-9-6f	Issue takeoff clearance to aircraft taking off behind a heavy jet/B757 at least 2 minutes after heavy jet/B757 begins takeoff roll
3min	3-9-7	When a small departs after a large or any aircraft departs after a heavy jet/B757 from an intersection on the same runway, 3 minutes between start of takeoff roll
4nmi	5-5-4d	Separate heavy behind heavy or large/heavy behind B757 by 4 nmi
5nmi	5-5-4d	Separate small behind B757 or small/large behind heavy by 5 nmi

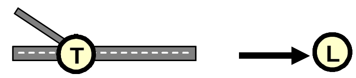
AB=Airborne

Single Runway: *Non-Visual In-Trail Departures*

Same Threshold In-Trail Departure

Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	3nmi	3nmi	3nmi	3nmi
Large	3nmi	3nmi	3nmi	3nmi
B757	2min or 5nmi	2min or 4nmi	2min or 4nmi	2min or 4nmi
Heavy	2min or 5nmi	2min or 5nmi	2min or 5nmi	2min or 4nmi

Intersection In-Trail Departure

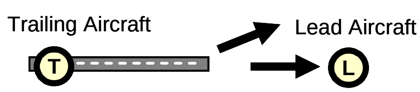


Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	3nmi	3nmi	3nmi	3nmi
Large	3min	3nmi	3nmi	3nmi
B757	3min	3min	3min	3min
Heavy	3min	3min	3min	3min

Rule Code	7110.65 Paragraph	Description
2min	3-9-6f	Issue takeoff clearance to aircraft taking off behind a heavy jet/B757 at least 2 minutes after heavy jet/B757 begins takeoff roll
3min	3-9-7	When a small departs after a large or any aircraft departs after a heavy jet/B757 from an intersection on the same runway, 3 minutes between start of takeoff roll
3nmi	5-5-4	Separate aircraft by 3 nmi when less than 40 nmi from radar antenna
4nmi	5-5-4d	Separate heavy behind heavy or large/heavy behind B757 by 4 nmi
5nmi	5-5-4d	Separate small behind B757 or small/large behind heavy by 5 nmi

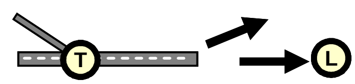
Single Runway: *Non-Visual Diverging (Fanned) Departures*

Same Threshold Diverging Departure



Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	1nmi	1nmi	1nmi	1nmi
Large	1nmi	1nmi	1nmi	1nmi
B757	2min or 5nmi	2min or 4nmi	2min or 4nmi	2min or 4nmi
Heavy	2min or 5nmi	2min or 5nmi	2min or 5nmi	2min or 4nmi

Intersection Diverging Departure

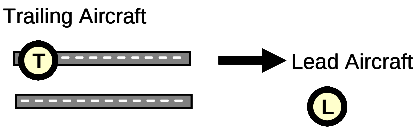


Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	1nmi	1nmi	1nmi	1nmi
Large	3min	1nmi	1nmi	1nmi
B757	3min	3min	3min	3min
Heavy	3min	3min	3min	3min

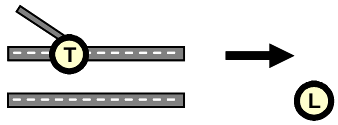
Note: the “6000 ft and Airborne” rule must still be applied for Large and Small aircraft for launching.

CSPR: *Visual Departures*

Even Threshold Departure



Displaced Threshold or Intersection Departure



Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	0	0	0	0
Large	0	0	0	0
B757	2min or 5nmi	2min or 4nmi	2min or 4nmi	2min or 4nmi
Heavy	2min or 5nmi	2min or 5nmi	2min or 5nmi	2min or 4nmi

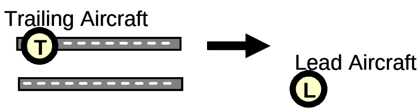
Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	0nmi	0nmi	0nmi	0nmi
Large	3min	0nmi	0nmi	0nmi
B757	3min	3min	3min	3min
Heavy	3min	3min	3min	3min

Rule Code	7110.65b Paragraph	Description
0nmi	3-8-3	Simultaneous same direction operation if runways at least 700 feet apart
2min	3-9-6f	Consider parallel runways less than 2500 feet apart as a single runway. Issue takeoff clearance to aircraft taking off behind a Heavy jet/B757 at least 2 minutes after Heavy jet/B757 begins takeoff roll
3min	3-9-7	When a Small departs after a Large or any aircraft departs after a Heavy jet/B757 from an intersection on the same runway, 3 minutes between start of takeoff roll
4nmi	5-5-4d	Separate Heavy behind Heavy or Large/Heavy behind 757 by 4 nmi
5nmi	5-5-4d	Separate Small behind B757 or Small/Large behind Heavy by 5 nmi

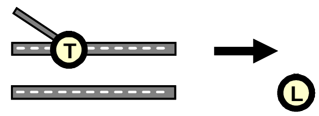
Comment: It should be noted, that although these are the rules at the runway, diverging courses or continued visual separation would be required before hand off to departure control. Continued visual separation is more an exception than the rule. Therefore, when diverging courses can not be provided, standard radar separation would usually be provided.

CSPR: *Non-Visual Same-Heading Departures*

Even Threshold Departure



Displaced Threshold or Intersection Departure



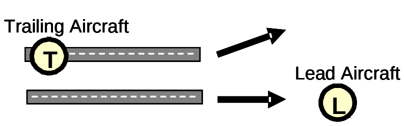
Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	3nmi	3nmi	3nmi	3nmi
Large	3nmi	3nmi	3nmi	3nmi
B757	2min or 5nmi	2min or 4nmi	2min or 4nmi	2min or 4nmi
Heavy	2min or 5nmi	2min or 5nmi	2min or 5nmi	2min or 4nmi

Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	3nmi	3nmi	3nmi	3nmi
Large	3min	3nmi	3nmi	3nmi
B757	3min	3min	3min	3min
Heavy	3min	3min	3min	3min

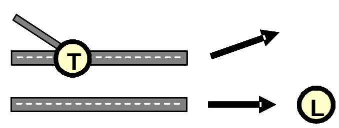
Rule Code	7110.65 Paragraph	Description
2min	3-9-6f	Issue takeoff clearance to aircraft taking off behind a heavy jet/B757 at least 2 minutes after heavy jet/B757 begins takeoff roll
3min	3-9-7	When a small departs after a large or any aircraft departs after a heavy jet/B757 from an intersection on the same runway, 3 minutes between start of takeoff roll
3nmi	5-5-4	Separate aircraft by 3 nmi when less than 40 nmi from radar antenna
4nmi	5-5-4d	Separate heavy behind heavy or large/heavy behind B757 by 4 nmi
5nmi	5-5-4d	Separate small behind B757 or small/large behind heavy by 5 nmi

CSPR: *Non-Visual Diverging (Fanned) Departures*

Even Threshold Departure



Displaced Threshold or Intersection Departure



Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	1nmi	1nmi	1nmi	1nmi
Large	1nmi	1nmi	1nmi	1nmi
B757	2min or 5nmi	2min or 4nmi	2min or 4nmi	2min or 4nmi
Heavy	2min or 5nmi	2min or 5nmi	2min or 5nmi	2min or 4nmi

Separation Rule Applied				
	Trailing Aircraft			
Lead Aircraft	**Small**	**Large**	**B757**	**Heavy**
Small	1nmi	1nmi	1nmi	1nmi
Large	3min	1nmi	1nmi	1nmi
B757	3min	3min	3min	3min
Heavy	3min	3min	3min	3min

Rule Code	7110.65 Paragraph	Description
2min	3-9-6f	Issue takeoff clearance to aircraft taking off behind a heavy jet/B757 at least 2 minutes after heavy jet/B757 begins takeoff roll
3min	3-9-7	When a small departs after a large or any aircraft departs after a heavy jet/B757 from an intersection on the same runway, 3 minutes between start of takeoff roll
1nmi	5-8-3	Separate successive departures by 1 nmi if courses diverge by 15 degrees or more
4nmi	5-5-4d	Separate heavy behind heavy or large/heavy behind B757 by 4 nmi
5nmi	5-5-4d	Separate small behind B757 or small/large behind heavy by 5 nmi

Note: 6000 feet and airborne must still be applied during launching between Small and Large aircraft

Appendix C

Cluster Assignments

This appendix summarizes the assignment of cluster for the 85 equipment types identified in Table C-1 for use in the benefit analysis for each of the 18 airports. The information in this table was extracted primarily from Jane's All The World's Aircraft [29].

Table C-1. Cluster Assignments of Equipment Types Used In Benefit Analysis

Equip	Number of Engines	Engine Type	Weight Class	Wing Span (m)	Max Wing Loading (kg/m^2)	Max T/O Wt. (kg)	Takeoff Speed (kts)	Max Landing Wt. (kg)	Touchdown Speed (kts)	Initial Wake Circ Strength (m^2/sec)	Lead Cluster
B742	4	J	H	59.64	739.4	377840	160	285765	130	376.1	1
B744	4	J	H	64.44	733.4	396895	160	285765	130	348.1	1
MD11	3	J	H	51.66	843.8	285990	169	218178	142	303.5	1
MD10	3	J	H	51.66	843.8	285990	169	218178	142	303.5	1
B772	2	J	H	60.93	670.6	286895	165	208650	130	268.8	1
DC10	3	J	H	50.4	705.6	263085	195	182798	148	250.1	1
A306	2	J	H	44.84	655.8	171700	170	140000	138	230.9	2
A30B	2	J	H	44.84	655.8	171700	170	140000	138	230.9	2
A310	2	J	H	43.9	748.9	164000	163	124000	126	228.8	2
B764	2	J	H	47.57	561.9	159210	160	136080	130	224.6	2
B763	2	J	H	47.57	561.9	159210	160	136080	130	224.6	2
B753	2	J	L	38.05	661.1	122470	160	101605	130	209.6	3
A321	2	J	L	34.09	694.4	89000	122	75500	110	205.5	4
B762	2	J	H	47.57	504.3	142880	160	123375	130	203.6	2
B752	2	J	L	38.05	625.6	115895	160	95255	130	196.5	3
DC8Q	4	J	H	45.23	583.9	158760	159	111130	140	179.1	2
MD83	2	J	L	32.87	630.5	72575	145	63275	115	170.8	4
MD90	2	J	L	32.87	696.6	78245	135	71210	130	170.1	4
MD82	2	J	L	32.87	589.1	67810	145	58965	115	159.2	4
MD81	2	J	L	32.87	551.7	67810	145	58060	115	156.7	4
MD80	2	J	L	32.87	551.7	67810	145	58060	115	156.7	4
B734	2	J	L	28.88	645.3	68040	139	56245	130	152.9	4

B738	2	J	L	34.31	632.1	79015	139	65315	130	149.4	5
B739	2	J	L	34.31	632.1	79015	139	65315	130	149.4	5
A319	2	J	L	34.09	616.8	75500	163	62500	126	148.5	5
B722	3	J	L	39.92	600.5	92124	144	75296	130	148.1	4
B72Q	3	J	L	39.92	600.5	92124	144	75296	130	148.1	4
A320	2	J	L	34.09	628.1	77000	155	64500	131	147.4	5
B733	2	J	L	28.88	595.8	62822	139	52890	130	143.8	5
B73Q	2	J	L	28.88	595.8	62822	139	52890	130	143.8	5
DC93	2	J	L	28.47	590.4	54885	135	49895	130	137.6	5
DC9Q	2	J	L	28.47	590.4	54885	135	49895	130	137.6	5
DC95	2	J	L	28.47	590.4	54885	135	49895	130	137.6	5
DC94	2	J	L	28.47	590.4	54885	135	49895	130	137.6	5
DC91	2	J	L	28.47	590.4	54885	135	49895	130	137.6	5
DC9	2	J	L	28.47	590.4	54885	135	49895	130	137.6	5
B735	2	J	L	28.88	574.3	60555	139	49895	130	135.6	5
B732	2	J	L	28.35	638.2	58105	139	48534	130	134.4	5
B737	2	J	L	34.31	555.2	69400	139	58605	130	134.1	5
BA46	4	J	L	26.34	545.7	42184	113	37648	110	132.6	5
B712	2	J	L	28.47	590.4	54885	139	47174	130	130.1	5
GLF4	2	J	L	23.72	383.2	33838	123	29937	104	123.8	6
CRJ7	2	J	L	23.24	495.7	34019	122	30390	108	123.6	6
F100	2	J	L	28.08	475.4	44450	135	39915	127	114.2	6
GLF3	2	J	L	23.72	364.1	31615	123	26535	104	109.8	6
DH8D	2	T	L	28.42	454.8	28689	108	27442	90	109.5	6
F900	3	J	L	19.33	421.2	21909	123	19050	104	96.7	6
CRJ2	2	J	L	21.21	440.8	24040	122	21319	108	94.97	6
E145	2	J	L	20.02	429.8	22000	122	19300	108	91.09	6
CRJ1	2	J	L	21.44	398.4	21523	122	20275	108	89.35	7
C750	2	J	S	19.38	330.7	16193	100	14424	86	88.31	8
E135	2	J	L	20.02	390.8	20000	122	18500	108	87.31	7
FA50	3	J	S	18.86	384.5	18007	123	16200	104	84.28	8
CL60	2	J	L	19.61	452.6	21863	122	17236	108	83.05	7
H25B	2	J	S	15.66	357.7	12430	119	10590	86	80.24	8
DH8C	2	T	L	27.43	347.0	19504	108	19050	90	78.74	7

AT43	2	T	L	24.57	341.3	18600	97	16700	89	77.93	7
F2TH	2	J	S	19.33	337.8	16556	123	14970	104	75.99	8
D328	2	T	S	20.98	349.8	13990	97	13230	89	72.3	8
DH8B	2	T	L	25.91	303.0	16465	108	15649	90	68.48	7
LJ60	2	J	S	13.34	433.8	10659	119	8845	100	67.66	8
SF34	2	T	L	21.44	314.6	13155	118	12930	91	67.63	7
DH8A	2	T	L	25.91	303.0	16465	108	15377	90	67.29	7
E120	2	T	S	19.78	304.1	11990	107	11700	90	67.07	8
C650	2	J	S	16.31	359.9	10432	100	9072	86	66	8
AT72	2	T	L	27.05	352.5	21500	140	21350	125	64.43	7
BE40	2	J	S	13.25	325.6	7303	100	7121	86	63.77	8
LJ45	2	J	S	14.57	316.5	9162	119	8709	100	61	8
J328	2	J	S	20.98	349.8	13990	122	13230	108	59.58	8
C56X	2	J	S	16.98	264.1	9071	100	8482	86	59.27	8
LJ35	2	J	S	12.04	347.1	8300	119	6940	100	58.82	8
C560	2	J	S	15.9	232.3	7393	100	6894	86	51.45	8
JS41	2	T	L	18.29	311.5	10150	120	9850	112	49.07	7
C550	2	J	S	15.9	223.8	6713	119	6123	86	45.69	8
MU2	2	T	S	11.95	296.0	4900	90	4655	95	41.84	8
B190	2	T	S	17.67	266.9	7688	120	7530	112	38.83	8
SW4A	2	T	S	14.1	219.7	5670	113	5670	107	38.35	8
SW4	2	T	S	14.1	219.7	5670	113	5670	107	38.35	8
BE20	2	T	S	16.61	201.4	5670	94	5670	91	38.28	8
JS32	2	T	S	15.85	273.8	6900	120	6600	112	37.94	8
C402	2	P	S	13.45	148.1	3107	87	3107	80	29.47	8
BE58	2	T	S	11.53	134.8	2495	87	2449	80	27.09	8
PA31	2	P	S	12.4	138.7	2948	90	2948	90	26.96	8
C208	1	T	S	15.88	139.8	3629	94	3538	91	24.98	8
C210	1	P	S	12.41	108.0	1860	87	1769	80	18.18	8

Glossary

AAR	Airport Acceptance Rate
ACARS	Aircraft Communications Addressing and Reporting System
ADR	Airport Departure Rate
ADS-B	Automatic Dependent Surveillance – Broadcast
aFAST	Active Final Approach Spacing Tool
AGL	Above Ground Level
AILS	Airborne Information for Lateral Separation
AIM	Aeronautical Information Manual
ALPA	Air Line Pilots Association
ARTCC	Air Traffic Control Center
ARTS	Automated Radar Terminal System
ASDE-X	Airport Surface Detection Equipment – Model X
ASPM	Aviation System Performance Measurements
ASQP	Airline Service Quality Performance
ATAAS	Advanced Terminal Area Approach Spacing
ATC	Air Traffic Control
ATCT	Air Traffic Control Tower
ATIS	Automated Terminal Information Service
ATL	The William B. Hartsfield Atlanta International Airport
AVOSS	Aircraft Vortex Spacing System
BCL	Baseline Capacity Limit
BOS	General Edward Lawrence Logan International Airport
CAASD	Center for Advanced Aviation System Development
CDTI	Cockpit Display of Traffic Information
CEF	Capacity Expansion Factor
C-EFR	CDTI Enhanced Visual Flight Rules
CHI	Computer Human Interface
CLE	Cleveland-Hopkins International Airport
CLT	Charlotte/Douglas International Airport
CPDLC	Controller Pilot Data Link Communications
CRDA	Converging Runway Display Aid
CSPR	Closely Spaced Parallel Runways
D-ATIS	Digital Automated Terminal Information Service
DFS	Deutsch Flugsicherung

DFW	Dallas-Ft. Worth International Airport
DROMS	Dynamic Runway Occupancy Monitoring System
DSS	Decision Support System
DTW	Detroit Metropolitan Wayne County Airport
EDR	Eddy Dissipation Rate
ETE	Estimated Time Enroute
ETMS	Enhanced Traffic Management System
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FMS	Flight Management System
GDP	Ground Delay Program
HMI	Human Machine Interface
IFALPA	International Federation of Air Line Pilots' Associations
IFR	Instrument Flight Rules
IGE	In Ground Effect
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
ITWS	Integrated Terminal Weather System
JFK	John F. Kennedy International Airport
LAX	Los Angeles International Airport
LDA	Localizer Type Directional Aid
LGA	LaGuardia Airport
LIDAR	Light Detection And Ranging
LLWAS	Low Level Windshear Alerting System
LNAV	Lateral Navigation
MAP	Missed Approach Point
MBRAF	Multiple Baseline Runway Adjustment Factor
MEM	Memphis International Airport
MIA	Miami International Airport
MSP	Minneapolis-St. Paul International Airport
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAID	Navigation Aid
OOOI	Out, Off, On, In
ORD	Chicago-O'Hare International Airport
PHL	Philadelphia International Airport

PRM	Precision Runway Monitor
RASS	Radio Acoustic Sounding System
RC	Runway Combination
RNP	Required Navigation Performance
RPAT	RNP Parallel Approach Transition
SDF	Louisville International – Standiford Field
SEA	Seattle-Tacoma International Airport
SFO	San Francisco International Airport
SODAR	Sound Detection and Ranging
SOIA	Simultaneous Offset Instrument Approaches
STARS	Standard Terminal Automation Replacement System
STL	Lambert St. Louis International Airport
TAF	Terminal Area Forecast
TAP	Terminal Area Productivity
TDWR	Terminal Doppler Weather Radar
TIS-B	Traffic Information System - Broadcast
TRACON	Terminal Radar Approach Control
TRL	Technology Readiness Level
TWIP	Terminal Weather Information for Pilots
VAMS	Virtual Airspace Modeling and Simulation
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VNAV	Vertical Navigation
WakeVAS	Wake Vortex Advisory System
WVWS	Wake Vortex Warning System

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14. ABSTRACT
The National Aeronautics and Space Administration (NASA) tasked The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) to investigate potential air traffic control (ATC) procedures that could benefit from technology used or developed in NASA's Wake Vortex Advisory System (WakeVAS). The task also required developing an estimate of the potential benefits of the candidate procedures. The main thrust of the investigation was to evaluate opportunities for improved capacity and efficiency in airport arrival and departure operations. Other procedures that would provide safety enhancements were also considered. The purpose of this investigation was to provide input to the WakeVAS program office regarding the most promising areas of development for the program. A two-fold perspective was desired: First, identification of benefits from possible procedures enabled by both incremental components and the mature state of WakeVAS technology; second identification of procedures that could be expected to evolve from the current Federal Aviation Administration (FAA) procedures. The evolution of procedures should provide meaningful increments of benefit and a low risk implementation of the WakeVAS technologies.

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aircraft spacing, aircraft wake vortex

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